Determining the Correlation Between Plantar Pressure and Joint Kinematics While Running

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DETERMINING THE CORRELATION BETWEEN PLANTAR PRESSURE AND JOINT KINEMATICS WHILE RUNNING

by

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ABSTRACT

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Running provides many health benefits, but there is a risk for lower extremity injuries. Previous studies have performed simultaneous assessments of plantar pressure and joint kinematics; however, they have not investigated correlations between these parameters. The goal of this study was to assess correlations between joint kinematics and plantar pressure metrics during the stance phase.

Fifteen female and eleven male recreational runners ran ten trials in this study. The joint kinematics were measured using the Vicon MX system and plantar pressure metrics were measured with the Quasar pressure treadmill. Spearman rho correlation tests were performed to determine correlations between joint kinematics and plantar pressure metrics. Mann-Whitney U tests were conducted to examine statistical differences between participant groups.

Females had positive correlations between peak plantar pressure and ankle dorsiflexion (DF), knee flexion, and ankle inversion and between speed and peak ground reaction force (GRF) for the entire foot. Male runners had correlations between peak knee flexion and plantar pressure, and between peak midfoot GRF and hip flexion. The males also had correlations between peak first metatarsal GRF and hip adduction, peak third metatarsal GRF and ankle DF, peak fourth metatarsal GRF and ankle DF, and peak fifth metatarsal GRF and knee flexion. Statistically significant differences were found in joint kinematics and plantar pressure metrics.

These correlations gave insight into risk factors for injury based on the relationship between plantar pressure metrics and joint kinematics. This information is helpful in determining proper treatment and preventive measures for running injuries.

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LIST OF ACRONYMS

3D	Three-dimensional
GRF	Ground reaction force
BW	Body weight
JRF	Joint reaction force
LE	Lower extremity
AP	Anterior-posterior
ML	Medial-lateral
COP	Center of pressure
IC	Initial contact
MSt	Midstance
TO	Toe-off
IS	Initial swing
MSw	Midswing
TS	Terminal swing
RFS	Rearfoot striking
MFS	Midfoot striking
FFS	Forefoot striking
COM	Center of mass
HF	Hindfoot
MF	Midfoot
FF	Forefoot
HL	Lateral heel
HC	Central heel
HM	Medial heel
M1	First metatarsal
M2	Second metatarsal
M3	Third metatarsal
M4	Fourth metatarsal
M5	Fifth metatarsal

CHAPTER 1: INTRODUCTION

1.1 CURRENT STATE OF THE PROBLEM

Running is a common form of exercise, providing health benefits such as weight loss, increased endurance, and improved cardiovascular health [1]. However, it also puts runners at risk for a myriad of lower extremity (LE) injuries. Incidence of LE injuries to each runner ranges from 19.3% to 79.3%. Multiple risk factors such as training regimen, age, gender, shoe design, and joint biomechanics contribute to the wide range [2, 3].

There have been multiple studies using simultaneous assessments of plantar pressure and joint kinematics to analyze running biomechanics. These studies examined how joint kinematics and plantar pressures change between different measurement tools, injury groups, running speed, and shoe design [4-12]. Pressure measuring insoles [4] have been proven as valid tools for measurement of vertical ground reaction forces (GRFs) and loading differences in running shoes [8]. They have also been used in the analysis of treadmill versus overground running [10] and influences of speed and cadence in treadmill running [9, 11]. Prior work showed that rearfoot strikers have greater average vertical loading rate and ankle dorsiflexion (DF) at initial contact than forefoot strikers [12]. Researchers showed that running in minimalist shoes leads to increased plantar pressure in the forefoot compared to non-minimalist shoes [6]. Another study reported the brand had no significant influence on plantar pressure, while low- and medium-cost running shoes had lower overall plantar pressure [7].

1.2 PURPOSE

There is limited research examining the correlations between plantar pressure parameters and joint kinematics. One study investigated how the pressure distribution is influenced by the foot strike pattern in healthy recreational runners. There was a significant interaction between a rearfoot strike pattern and peak plantar pressure under the heel, concluding that rearfoot striking is associated with greater peak plantar pressure in the heel [13]. This current study will show relationships that exist between plantar pressure parameters and joint kinematics between female and male recreational runners. The goal of this study was to determine correlations between joint kinematics and plantar pressure parameters during the stance phase of running. Assessing how these parameters are correlated can provide novel information on potential injury risk factors for recreational runners.

To achieve the study goal, plantar pressure data was collected with a Quasar pressure treadmill (Noraxon USA Inc.; Scottsdale, AZ), which is an alternative to instrumented force treadmills. Force treadmills are a common research tool for kinetic analysis during running. They are constructed with six-axis force plates embedded in the belt of the treadmill, which allows for continuous measurement of forces during assessment [14]. Plantar pressure treadmills are an alternative with decreased cost, increased portability, and lack of required dedicated lab space. These treadmills measure center of pressure (COP) and use its magnitude and x-y location to calculate vertical GRFs. A disadvantage of these treadmills is that shear forces are not calculated, which eliminates braking and propulsion forces.

1.3 HYPOTHESIS AND SPECIFIC AIMS

The plantar pressure parameters examined in this study were peak plantar pressure and vertical ground reaction force (GRF) for the entire foot, peak GRF and force impulse in three zones of the foot (hindfoot, midfoot, and forefoot), and peak GRF and force impulse in ten zones of the foot (medial heel, central heel, lateral heel, midfoot, metatarsals 1-5, and toes). Joint kinematics examined in this study were sagittal plane motion of the ankle, knee, and hip and coronal plane motion of the ankle and hip. It was hypothesized there are correlations present between peak plantar pressure (entire foot) and peak GRF (entire foot, foot divided into three zones, foot divided into ten zones) and the joint kinematic parameters. This hypothesis was tested by the following specific aims:

1) Collected kinetic and kinematic data using a plantar pressure treadmill and motion analysis of healthy recreational runners.
2) Calculated parameters related to plantar pressure and joint kinematics during the stance phase of running.
3) Compared running kinematics to published data.
4) Performed correlation tests between plantar pressure parameters and joint kinematics.

CHAPTER 2: LITERATURE REVIEW

2.1 INCIDENCE OF INJURY

The per runner incidence of LE injuries during running ranges from 19.3% to 79.3% [2, 3]. This wide range of injuries is a result of intrinsic and extrinsic risk factors. Intrinsic risk factors contributing to running injuries include anatomy, gender, and age. Some extrinsic risk factors that contribute to running injuries are training, stretching, running shoe design, and gait pattern [15]. Lower extremity running injuries are described as overuse, strains, or sprains. Overuse injuries occur when the LE joints are repeatedly exposed to high forces during running, whereas acute injuries are sudden and severe. Strains are a result of over-stretched or torn muscles or tendons and sprains are a result of over-stretched or torn ligaments [16-18]. Stress fractures can develop from either severe bruising or tiny cracks in the bone because of repetitive force. They occur in 0.7% of the general population but have an incidence rate of 13% in female and 8% in male runners [19, 20]. Table 2.1.1 summarizes common running injuries at the LE joints.

Table 2.1.1 Common running injuries at each LE joint. Injuries listed for the ankle joint include injuries to the foot. Causes of the running injuries are listed as overuse or acute. Incidence of injuries are also listed and represent only the most common running injuries for the joint.

Joint	**Running Injuries**	**Causes**	**Incidence**
Hip	Hip osteoarthritis [15]	Overuse	3.5% [22]
	Femoral neck stress fracture [15]	Overuse	4% [23]
	Hamstring strains [21]	Overuse or acute	10.9% [24]
	Acetabular labral tears [15, 21]	Acute	5% [25]
	Iliopsoas tendinopathy [15]	Acute	6.6% [3]
	Sports hernia [21]	Acute	6.2% [26]

Joint	Running Injuries	Causes	Incidence
Knee	Patellofemoral pain [15, 27, 28]	Overuse	17% [23]
	Iliotibial band syndrome [15, 21]	Overuse	6%
	Knee osteoarthritis [15]	Overuse	3.5% [22]
	Medial tibial stress syndrome [15, 27]	Overuse	8% [23]
	Chondromalacia patella [28]	Acute	5.5% [24]
	Knee sprains [29, 30]	Acute	5%
Ankle	Plantar fasciitis [15]	Overuse	7% [23]
	Navicular stress fractures [15]	Overuse	4%
	Metatarsal stress fractures [15]	Overuse	4%
	Achilles tendinitis [27, 28]	Acute	10%
	Posterior tibialis tendinitis [15]	Acute	6.6% [3]
	Anterior tibialis tendinitis [15]	Acute	6.6%
	Ankle sprains [29]	Acute	5.1%

Strike patterns present different running injury risks. There are three defined patterns: rearfoot (RFS), midfoot (MFS), and forefoot (FFS). Rearfoot striking runners will contact the ground with the heel first, where MFS runners will have initial contact (IC) at the midfoot. In FFS running, the runner will contact the ground with their forefoot [31, 32]. The striking patterns present significant differences in sagittal plane motion at the ankle and knee joints. There is a greater dorsiflexion (DF) angle but lower knee flexion at IC for RFS runners than FFS runners [32]. Prior research has shown significantly lower peak knee abduction (ABD) moment for FFS runners [33].

The hip is a classic ball-and-socket joint and is defined as the articulation between the femoral head and acetabulum. Injuries to the hip make up 11.5% of all running injuries but are difficult to diagnose because of the complex anatomy of the joint [34, 35]. Hip osteoarthritis (OA) occurs when the cartilage in the joint degenerates over time. Prior research has shown that running mileage and pace may contribute to the cartilage degeneration [36, 37]. Runners with hip OA describe pain as deep and radiating anteriorly in the joint and present decreased hip range of motion (ROM), especially in the transverse plane [15]. Another hip injury seen in runners is a femoral neck stress fracture. These fractures develop from repeated microtrauma of the femoral neck [38], leading to limited hip internal rotation (IR), adduction (ADD), or flexion. Hamstring strains are a type of running injury that are described as sudden, sharp pain in the posterior thigh. The injury occurs when the hamstrings are eccentrically contracting as the quadriceps are concentrically contracting, over-stretching the muscles. Hamstrings are responsible for knee flexion and hip extension, so if injured, these motions are limited [39]. Additional acute running injuries of the hip include acetabular labral tears, iliopsoas tendinopathy, and sports hernia. Runners with acetabular labral tears and iliopsoas tendinopathy express anterior hip pain, while those with sports hernia describe pain in the groin. Forceful hip rotation or flexion are examples of biomechanical risk factors for iliopsoas tendinopathy, sports hernias, and acetabular labral tears [15].

Fifty percent of LE running injuries occur at the knee. One of the most common running knee injuries is patellofemoral pain [40]. It is commonly described as anterior knee pain. Risk factors include excessive hip adduction (ADD), decreased knee extension moment and flexion angle. The incidence of patellofemoral pain can be as high as 40%, but the ratio of incidence between females and males is 2:1. The higher incidence in female runners is due to them having significantly lower peak knee ADD as well as greater peak hip ADD and peak hip IR than male runners. These differences lead to increased loading on the lateral aspect of the knee [41]. Increased knee ABD impulses have also been reported as a risk factor for patellofemoral pain syndrome in RFS runners due to the increased loading in the medial knee [33, 42]. Decreased knee extension moment and knee flexion are thought to be used as a compensating mechanism to decrease contact between the patella and trochlear groove of the femur [43]. Iliotibial (IT) band syndrome is a common running injury where pain develops in the IT band at the lateral femoral epicondyle. Biomechanical risk factors contributing to IT band syndrome include genu varum and increased hip abduction (ABD) during the stance phase. Over time, this can lead to irritation of the tissue at the lateral femoral epicondyle and iliac crest [44]. Knee OA is another running injury where repetitive high joint loading leads to deterioration of the articular cartilage between the femoral and tibial condyles. Risk factors for knee OA include obesity, previous knee injuries, and a family history of the injury [15, 45]. Chondromalacia patella, also called "runner's knee," develops when the articular cartilage on the posterior surface of the patella softens and deteriorates. It is seen when there is a strength imbalance between the hip ADD and ABD muscles or weak hamstrings and quadriceps. Another running knee injury is medial tibial stress syndrome; characterized by diffuse pain through the tibial shaft. It is commonly associated with excessive pronation during midstance (MSt) [15, 27]. Another common knee running injury is knee sprain; classified as grade I (mild), II (moderate), or III (severe). The causes of knee sprains are dependent on which ligament is injured.

The ankle is a complex joint structure of the lower extremities. Running injuries of the ankle and foot occur at a rate of 16.6% and 39.3%, respectively, and are most common among marathon and long-distance runners [46]. Ankle sprains are a common running injury, with lateral sprains being the most common type. The mechanism of injury for lateral sprains is excessive inversion while plantar flexed (PF) at initial contact (IC) or toe-off (TO), causing over-stretching of the calcaneofibular and talofibular ligaments [47]. Another injury is plantar fasciitis, described as pain in the plantar region of the foot. Risk factors for plantar fasciitis include excessive PF at TO, as seen in FFS runners, and excessive pronation at IC [15, 48]. Stress fractures of the navicular bone and metatarsals are also injuries of concern for runners. Limited ankle PF is a risk factor for navicular stress fractures [5], while risk factors for metatarsal stress fractures include excessive ankle PF during TO [49] and increased forefoot plantar pressure while wearing minimalist running shoes [6]. Additional running injuries of the ankle and foot are tendinitis of the Achilles tendon and anterior and posterior tibialis. These injuries are often due to sudden increases in training intensity. Excessive pronation at IC, poor tendon flexibility, and valgus or varus calcaneus deformity are risk factors for Achilles tendinitis, potentially increasing the torque of the tendon. For FFS runners, there is a significantly greater ankle PF moment compared to RFS runners, presenting an increased risk for metatarsal stress fractures, Achilles tendinopathy, and plantar fasciitis [33, 50]. Posterior tibialis tendinitis is often described as pain just inferior to the medial malleolus and is associated with excessive pronation. Runners with anterior tibialis tendinitis express anterior ankle pain, which increases with limited ankle DF [15].

2.2 BIOMECHANICS OF RUNNING

2.2.1 PHASES OF THE RUNNING CYCLE

There are two main phases of the running cycle: stance and swing (Figure *2.2.1.1*). The stance phase makes up about 40% of the running cycle [51]. This phase can be subdivided into initial contact (IC), midstance (MSt), and toe-off (TO). Initial contact is defined from foot contact through the first 10% of the cycle. The body then progresses forward over the planted foot, marking the MSt period. Between IC and MSt, there is an absorption period, during which the lower extremities absorb the GRF. Toe-off occurs when the foot leaves the ground and marks the end of the stance phase. The propulsion period occurs between MSt and TO and is defined as the period when the foot is getting ready to leave the ground and push into swing phase [51, 52].

Swing phase makes up the last 60% of the running cycle and is subdivided into three phases: initial swing (IS), midswing (MSw), and terminal swing (TS). Initial swing is defined as the period where the leg is being swung backward. During MSw, the leg is still being swung backward but decelerates to start bringing the leg forward. In TS, the leg is being brought forward and preparing for the next IC. The swing phase is also marked by two double float periods that occur when both feet are off the ground during IS and TS [51, 52].

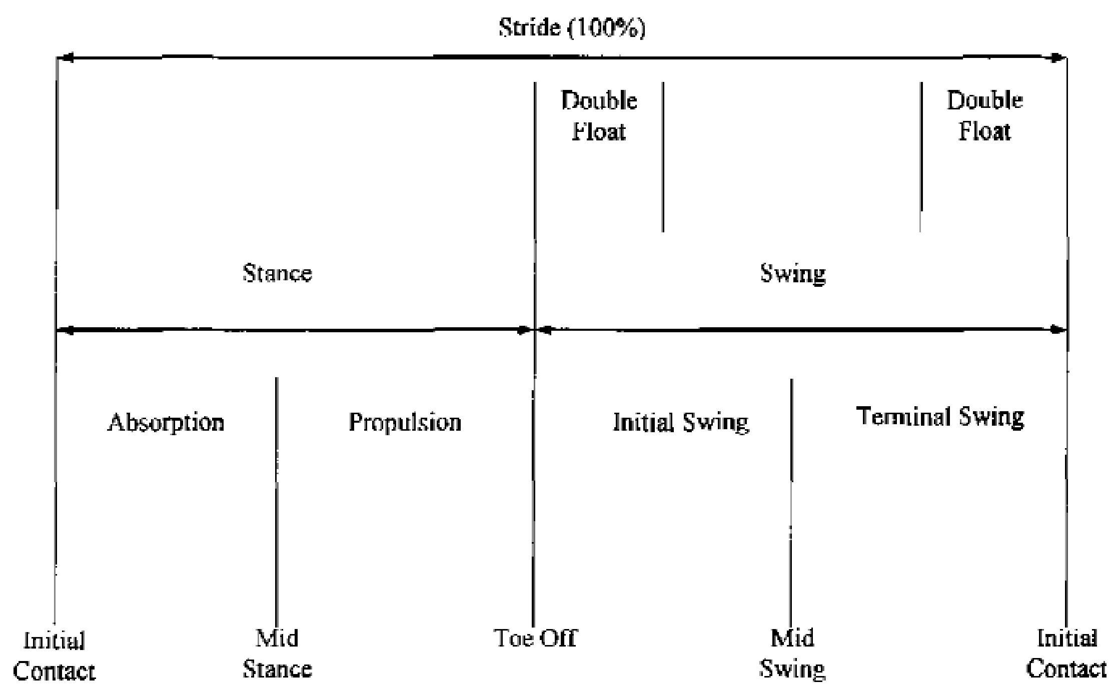

Figure 2.2.1.1 Events of the running cycle. From Thordarson, D.B. with permission [51].

2.2.2 SPATIO-TEMPORAL PARAMETERS

Spatio-temporal parameters for running are measurements of distance and time defined for one cycle (**Error! Reference source not found.**). These parameters can be used to assess running stride efficiency and injury risk.

Table 2.2.2.1 Spatio-temporal parameters during a running cycle [52, 53].

Parameter	**Definition**
Stride length	Distance traveled from initial contact to next initial contact of ipsilateral foot
Step length	Distance traveled from initial contact to toe-off of ipsilateral foot
Stance time	Time between initial contact to toe-off of ipsilateral foot
Swing time	Time between toe-off and next initial contact of ipsilateral foot
Step time	Time between initial contact and next initial contact
Aerial time	Time during double float period of swing phase
Cadence	Number of steps per minute
Running speed	Distance covered over a period of time

2.2.3 KINEMATICS

The term kinematics is defined as the movement of joints in three anatomic orthogonal planes (sagittal, coronal, and transverse), independent of their forces (Figure 2.2.3.1) [51, 53]. Movement within the three planes are inter-related and remain the same for each stride [51].

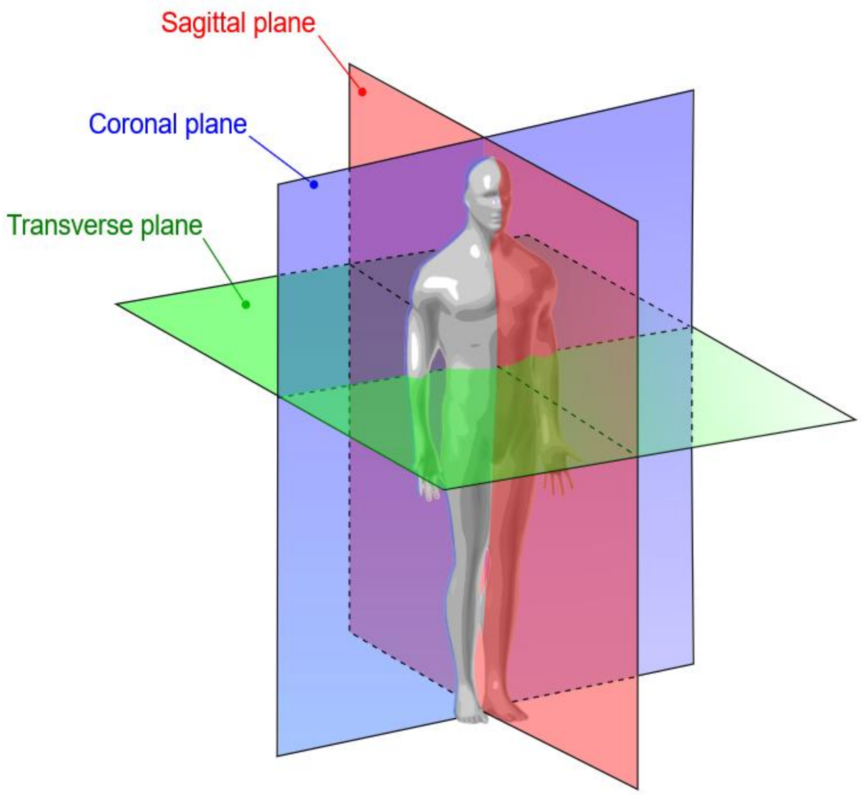

Figure 2.2.3.1 Three anatomic orthogonal planes: sagittal, coronal, and transverse. The sagittal plane (red) divides the body into left and right sides. The coronal plane (blue) divides the body into anterior and posterior sections. The transverse plane (green) divides the body into superior and inferior sections. From Medicine LibreTexts with permission from the Creative Commons License [54].

To accurately describe LE kinematics, the LE joint positions must be clearly defined. Proximal and distal segments of the hip are the pelvis and thigh, respectively. The thigh and shank are the respective proximal and distal segments for the knee. The ankle joint is defined by the shank and foot segments. Joint kinematics are defined as the position of the distal segment relative to the joint's proximal segment. The pelvis segmental motion and foot progression angles are defined relative to the global coordinate system of the laboratory [52].

There are specific actions that occur in each plane for every LE joint. Sagittal plane ankle motion are DF and PF. At the knee and hip, the sagittal plane motions are flexion and extension. Anterior and posterior tilt are the pelvic sagittal plane motions. The coronal plane movements at the ankle are inversion and eversion. Coronal plane knee and hip motions are termed abduction (ABD) and adduction (ADD). However, the coronal plane knee motion is commonly referred to valgus and varus. Pelvic obliquity represents the coronal plane motion of the pelvis. Transverse plane movements of the LE joints and pelvis are internal rotation (IR) and external rotation (ER) [53, 55, 56]. The following sections explain normal running kinematics for the LE joints and pelvis in all three planes.

2.2.3.1 ANKLE KINEMATICS

If a runner has a RFS pattern, the ankle is DF about 0-5° at IC and continues to DF to about 30° near MSt. The ankle then starts to PF between 10-20° until TO. During swing, the ankle slowly DF to 10° and gradually PF to prepare for the next foot contact [53]. In the coronal plane at IC, the ankle can range between 5° of inversion and 10° of eversion. The ankle everts and reaches its peak eversion between 5° and 20° at 16% of the running cycle [52, 56]. In the transverse plane, the foot is in IR. Then, the foot ER from MSt until TO. The foot is in IR for most of the swing phase. In TS, the foot slightly ER then IR to prepare for the next IC [31, 53].

Figure *2.2.3.1.1* shows typical 3D ankle kinematics during one running cycle.

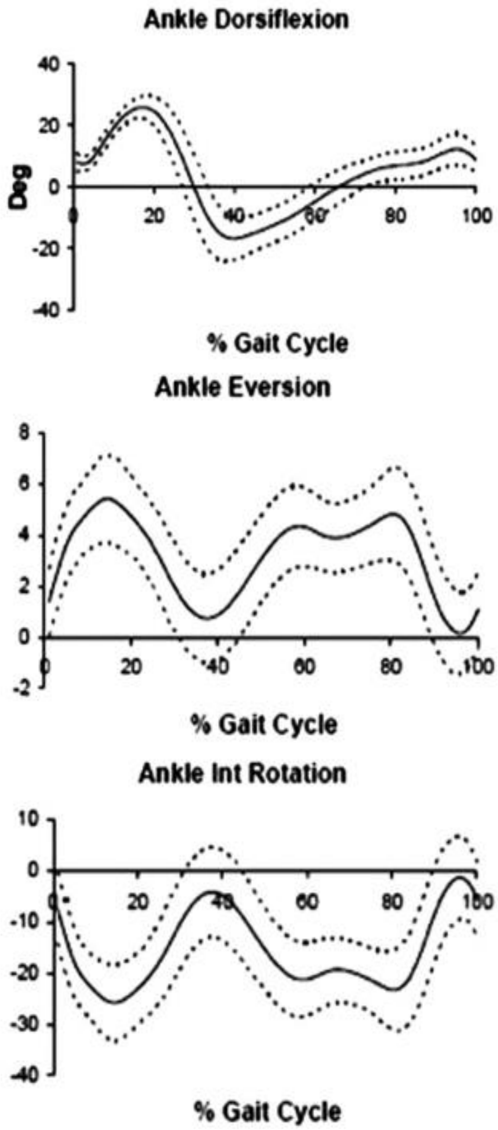

Figure 2.2.3.1.1 Kinematics of the ankle during one running cycle: sagittal plane (top graph), coronal plane (middle graph), and transverse plane (bottom graph). The dotted lines represent ± 1 standard deviation. The x-axis is in percent of stride and y-axis is in degrees. From Dicharry, J. with permission [31].

2.2.3.2 KNEE KINEMATICS

In the stance phase, the knee flexes to 45° during the absorption period and extends 25° until the end of the propulsion period (

Figure *2.2.3.2.1*). During swing, the knee flexes to 90° but can reach up to 130° depending on running speed [52, 53, 56]. Knee motion in the coronal plane is minimal, averaging about 5° of ABD and ADD (

Figure *2.2.3.2.1*). In the transverse plane, the knee internally rotates between 5° and 10° for the first half of stance phase. The knee externally rotates the same amount in the second half of stance (

Figure *2.2.3.2.1*) [53].

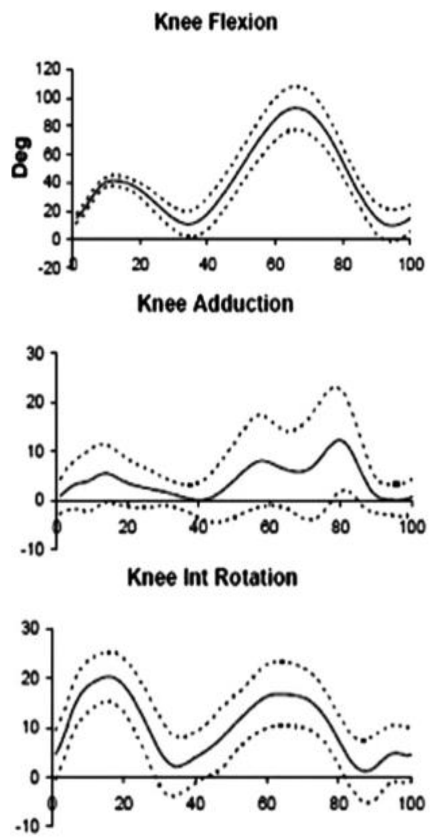

Figure 2.2.3.2.1 Kinematics of the knee during one running cycle: sagittal plane (top graph), coronal plane (middle graph), and transverse plane (bottom graph). The dotted lines represent ± 1 standard deviation. The x-axis is in percent of stride and y-axis is in degrees. From Dicharry, J. with permission [31].

2.2.3.3 HIP KINEMATICS

For the first 10% of stance, the hip is in flexion and then extends for the rest of the phase, reaching a max extension at TO (Figure 2.2.3.3.1). During swing, the hip is in flexion until it reaches its maximum value at TS. From TS until the next IC, the hip is in extension to prevent excessive deceleration that would occur if the foot was ahead of the body's center of mass (COM) during IC [53].

During IC, the hip is slightly adducted and continues to adduct until it reaches its maximum ADD angle of 8-10° before MSt (Figure 2.2.3.3.1). From MSt to IS, the hip is in ABD. The hip abducts through MSw. Once in TS, the hip returns to ADD to prepare for the next IC. Coronal plane hip motion is a shock absorbing mechanism like the one seen in the sagittal plane motion of the knee and ankle [52, 53].

In the transverse plane, the hip is externally rotated during IC but internally rotates throughout the rest of stance phase (Figure 2.2.3.3.1). During TO, the hip slightly externally rotates and then internally rotates until TS. In TS, the hip externally rotates to prepare for the next IC [53, 56].

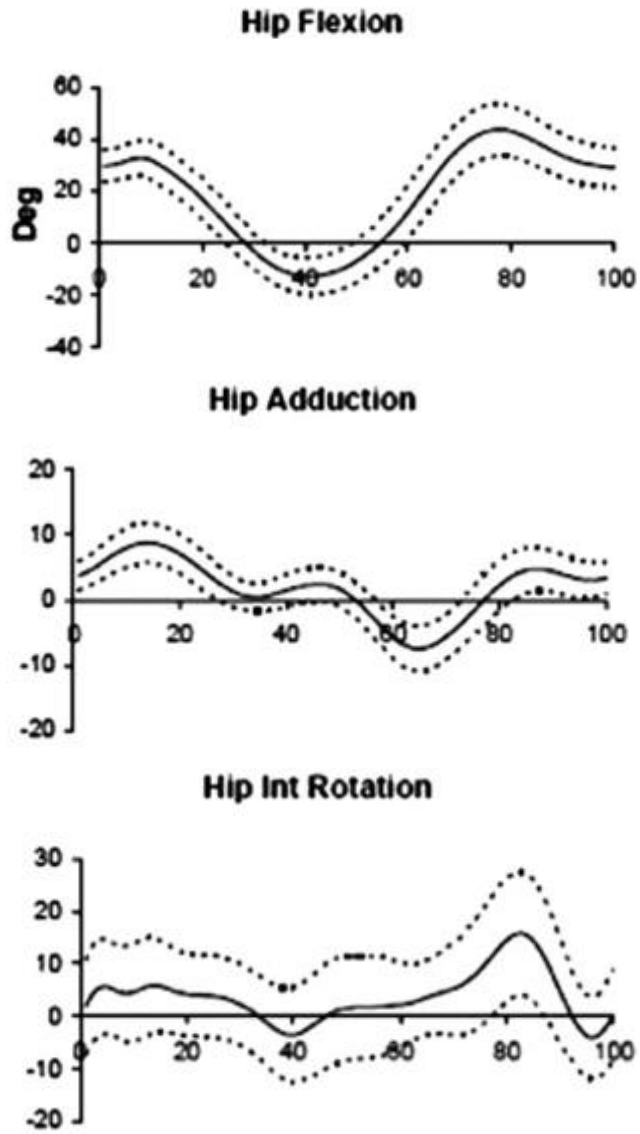

Figure 2.2.3.3.1 Kinematics of the hip during one running cycle: sagittal plane (top graph), coronal plane (middle graph), and transverse plane (bottom graph). The dotted lines represent ± 1 standard deviation. The x-axis is in percent of stride and y-axis is in degrees. From Dicharry, J. with permission [31].

2.2.3.4 PELVIS KINEMATICS

Sagittal plane pelvic motion is represented by anterior and posterior tilt. Range of motion is between 5° and 7°, with a net tilt of 10° (Figure 2.2.3.4.1) [52, 53, 56].

During IC, there is a contralateral (CL) lateral pelvic tilt, which is when the iliac crest of the stance limb is raised upwards. This tilt reaches its maximum position just before MSt. The pelvis switches to an ipsilateral (IL) lateral tilt until TO, where it reaches its maximum position. This cycle repeats during the swing phase (Figure 2.2.3.4.1) [53].

In the transverse plane, IR and ER of the pelvis is determined by the direction of the iliac crest of the stance limb. When iliac crest is rotated forward, the pelvis is internally rotated. The pelvis is in ER when the iliac crest is rotated backwards. At IC, the pelvis externally rotates until it reaches its maximum position just before MSt. Between MSt and TO, the pelvis internally rotates to a neutral position. During swing phase, the pelvis is in IR until reaching a maximum position at MSw. The pelvis externally rotates for the rest of swing to prepare for the next IC (Figure 2.2.3.4.1) [53].

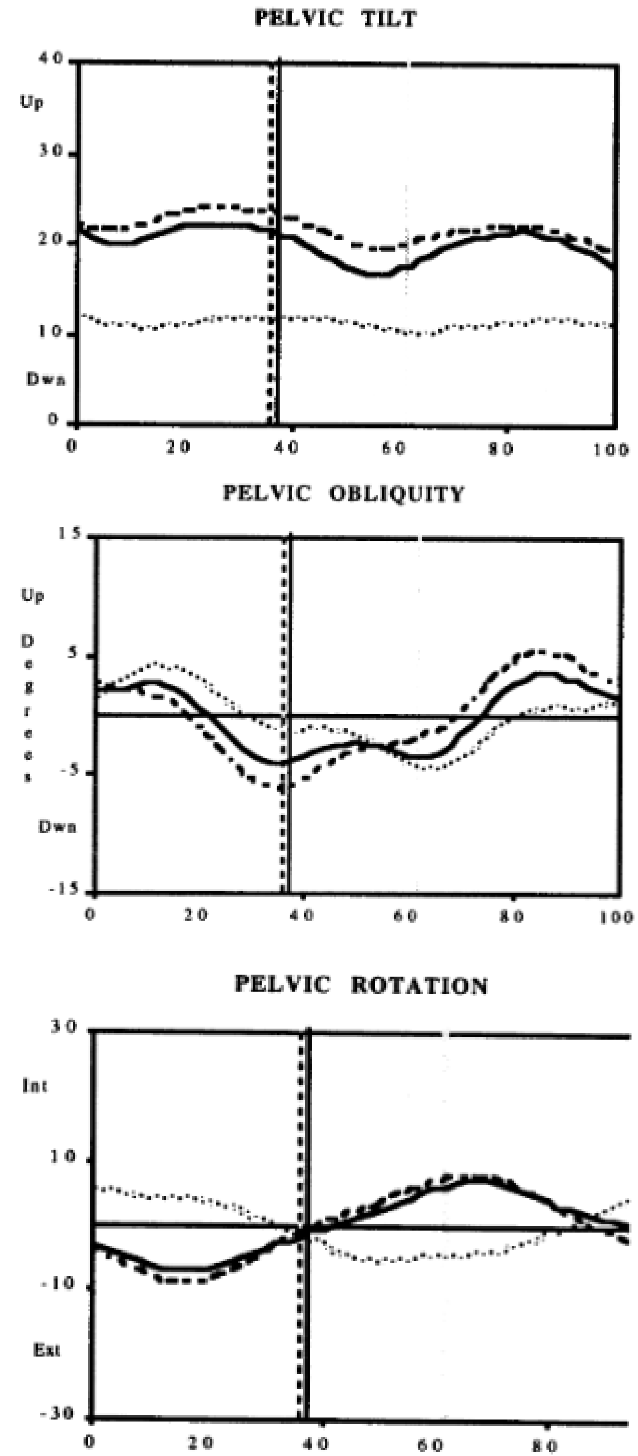

Figure 2.2.3.4.1 Kinematics of the pelvis for one running cycle during three activities: walking (light dash line), running (solid line), and sprinting (dark dash line). Vertical line indicates toe-off into swing phase. The x-axis is in percent of stride and y-axis is in degrees. From Novacheck, T.F. with permission [53].

2.2.4 KINETICS

The term kinetics is defined as the study of internal and external forces that cause motion. External forces that cause motion during running are GRFs. Internal forces occur within the body are a result of muscular forces or tension in connective or soft tissues [51, 56, 57]. These forces contribute to calculating joint reaction forces (JRFs), moments, and powers of the LE joints. The kinetics during running are used to make inferences on causes of injury.

The following sections explain the three components of the GRF and normal, 3D running kinetics for the LE joints. The joint kinetics described will be the joint moments and powers. Moments will be explained as internal moments and powers will be described as either being generated or absorbed.

2.2.4.1 GROUND REACTION FORCES

The GRF has components in the vertical, anterior-posterior (AP), and medial-lateral (ML) directions (

Figure *2.2.4.1.1*).

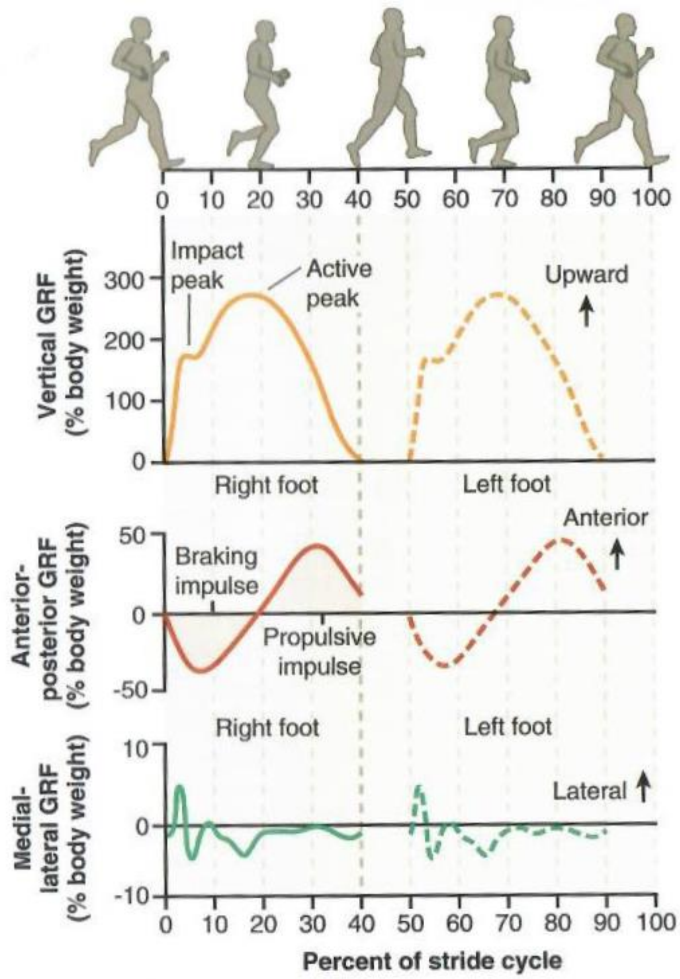

Figure 2.2.4.1.1 The components of the GRF during running: vertical (top graph), anterior-posterior (AP) (middle graph), medial-lateral (ML) (bottom graph). From Neumann, D. with permission [56].

The vertical GRF is the largest component of the GRF, reaching as high as 3-4 times body weight (BW) [51]. This GRF component has two peaks during a running stride: the impact peak and the active peak. The impact peak indicates the moment the foot contacts the ground and goes in a distal-to-proximal direction. Magnitude of this peak reaches up to 1.5 times BW and changes with running surface, striking pattern, and cadence [56]. The active peak occurs during MSt with a magnitude between 2.2 and 4 times BW and is affected by leg stiffness and landing velocity [31, 51, 56]. When the active peak occurs, the AP GRF is equal to 0 times BW and the body is preparing for TO. The active peak corresponds with maximum magnitude of the external forces contacting the body, causing an internal force generation to balance the response [31, 56].

The second largest component of the GRF occurs in the AP direction, with a magnitude of 0.25-0.50 times BW. This component is affected by a runner's striking pattern, speed, cadence, and running surface. In the first half of stance, the AP GRF is directed posteriorly as a braking force, decelerating anterior progression of the COM. If braking forces are high, then COM is behind the feet during IC. Braking force increases when running downhill and decreases when running uphill. The AP GRF is pointed anteriorly in the second half of stance, corresponding with the propulsion period as the body prepares to go into the swing phase. The active peak of the vertical GRF corresponds when the body's COM begins accelerating for TO. Propulsion force increases when running uphill and decreases when running downhill [31, 56].

The ML GRF is the most variable between runners and lowest in magnitude (0.05-0.15 times BW) of the three components. This GRF component measures the path of the body's COM in the coronal plane and represents the stability of the runner during the running cycle. Variability in ML GRF is due to differences in foot types and striking patterns [58]. If ML COM deviation is high, there is an increase in the internal torque that is required to counteract the external torque. High COM deviations are seen in runners who do not have a strong core or hip abductors, leading to poor core and hip stability. However, researchers have not found an increased injury risk associated with high COM deviations [15, 31, 56, 59].

2.2.4.2 ANKLE KINETICS

During stance, the ankle is in a PF moment (Figure 2.2.4.2.1). The power of the joint is being absorbed from 0-20% of the cycle because the PF muscles are eccentrically active to control tibial advancement. For the second half of stance, the PF muscles are concentrically active to generate power in the ankle and help the leg propel into swing phase. From IS to MSw, there is a slight DF moment in the ankle to help clear the foot as the leg is swinging forward. At the same time, power is generated by concentric activation of the DF muscles. The ankle kinetics in the coronal and transverse planes are minimal (Figure *2.2.4.2.2*) [53, 56].

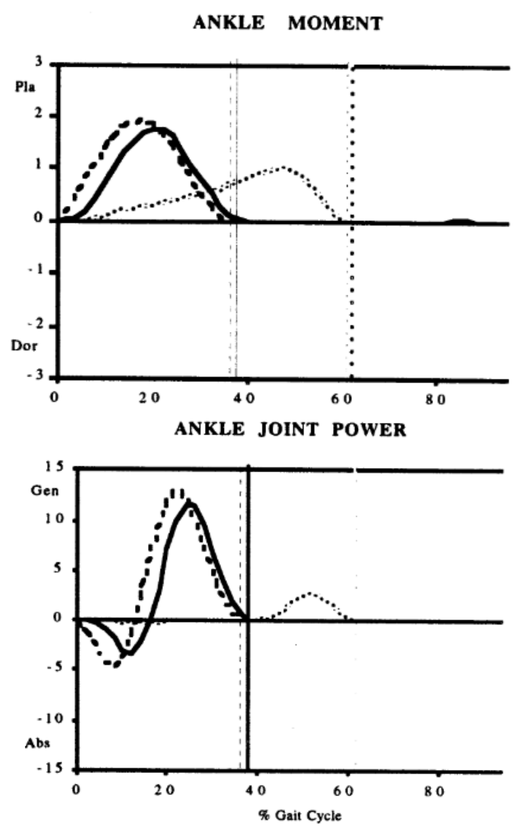

Figure 2.2.4.2.1 Sagittal plane ankle internal moment (top) and power (bottom). The x-axis is in percent of stride. The y-axis for the moment graph is in (N-m)/kg and for the power graph is in W/kg. From Novacheck, T.F. with permission [53].

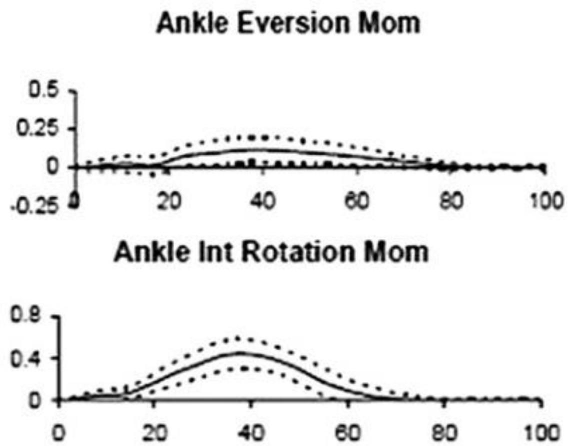

Figure 2.2.4.2.2 Internal ankle moments of the coronal plane (top) and transverse plane (bottom). The x-axis is in percent of stance and the y-axis is in (N-m)/kg. From Dicharry, J., with permission [31].

2.2.4.3 KNEE KINETICS

At IC, there is a slight knee flexion moment present (Figure 2.2.4.3.1). This moment is representative of the knee flexors concentrically contracting to help with shock absorption. For the rest of stance, the knee has an extension moment. From 5-15% of stance, the knee absorbs power to control flexion. Once in MSt, the knee generates power by concentrically contracting the quadriceps until TO. The knee continues to have an extension moment and absorb power in IS. This is necessary to slow down the amount of knee flexion and prevent the leg from rapidly kicking back. As the leg swings forward during MSw and TS, there is a flexion moment to decelerate knee extension. For most of this period, the knee is absorbing power to prepare the knee for the next IC [53, 56].

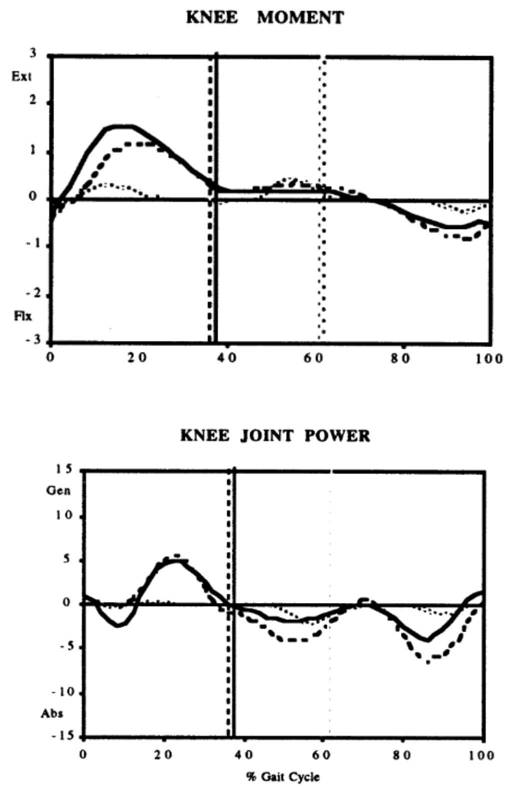

Figure 2.2.4.3.1 Sagittal plane internal knee moment (top) and power (bottom). The x-axis is in percent of stride. The y-axis for the moment is in (N-m)/kg and for the power is in W/kg. From Novacheck, T.F., with permission [53].

There is minimal coronal plane motion at the knee during running (Figure 2.2.4.3.2). However, the knee has an internal ABD moment present in stance. The power generated and absorbed in the stance phase is oscillatory. During swing phase, the internal moment hovers around zero. Knee power absorption is equivalent to the power generated [53, 56]. In the transverse plane, the knee has very minimal internal moment and power (Figure 2.2.4.3.3). However, there is a slight ER moment during the MSt period of the stance phase [56].

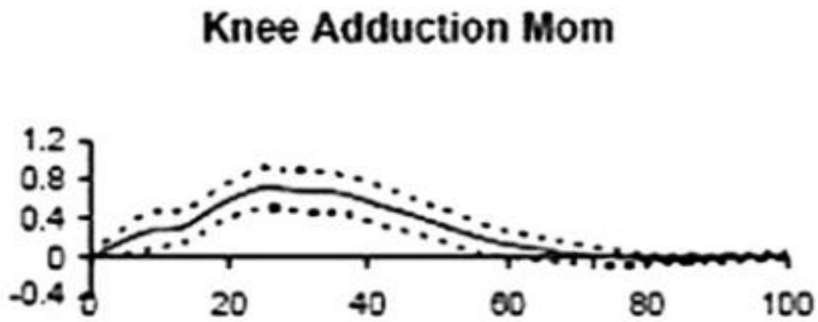

Figure 2.2.4.3.2 External coronal plane moment for the knee. The x-axis is in percent of stance and y-axis is in (N-m)/kg. From Dicharry, J. with permission, [31].

Figure 2.2.4.3.3 Transverse plane external knee moment. The internal moment at the knee is an external rotation moment during the stance phase. The x-axis is in percent of stance and y-axis is in (N-m)/kg. From Dicharry, J. with permission, [31].

2.2.4.4 HIP KINETICS

From IC to MSt, the hip produces an extension moment (

Figure *2.2.4.4.1*). This moment provides vertical COM support and help the hip extend during IC. Power is generated because of this extension moment. From MSt to MSw, a flexion moment is produced at the hip. Between MSt and TO, power is absorbed at the hip to decelerate hip extension. From IS to MSw, power is generated from concentric contraction of the hip flexors to help advance the hip forward. The hip joint produces an extension moment and generates extension power from MSw through the end of the running cycle. Since the hip is in flexion during this time period, the power generated decelerates hip flexion and initiates hip extension to prepare for the next IC [53, 56].

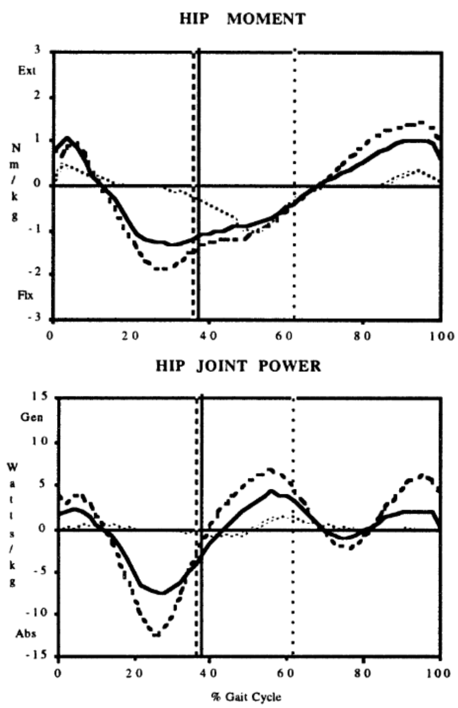

Figure 2.2.4.4.1 Sagittal plane hip internal moment (top) and power (bottom). The x-axis is in percent of stride. The y-axis for the moment is in (N-m)/kg and for the power is in W/kg. From Novacheck, T.F. with permission, [53].

From 0-40% of stance, there is an internal ABD moment produced at the hip (Figure 2.2.4.4.2). During IC, power is absorbed by the eccentric activation of the hip abductors to lower the CL side. Power is then generated by concentric contraction of the hip abductors to raise the CL side until TO. During swing phase, the coronal plane moment and power oscillate around zero [53, 56].

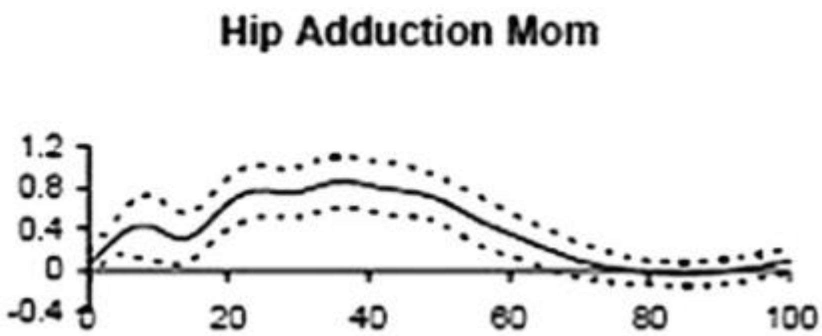

Figure 2.2.4.4.2 Coronal plane external hip moment. The x-axis is in percent of stance and y-axis is in (N-m)/kg. From Dicharry, J. with permission [31].

There is an IR moment at the hip from 0-30% of the stride in the transverse plane (Figure 2.2.4.4.3). At the same time, power is generated at the hip to the IL iliac crest can rotate forward. For the rest of running cycle, the hip rotation moment and power are around zero [53, 56].

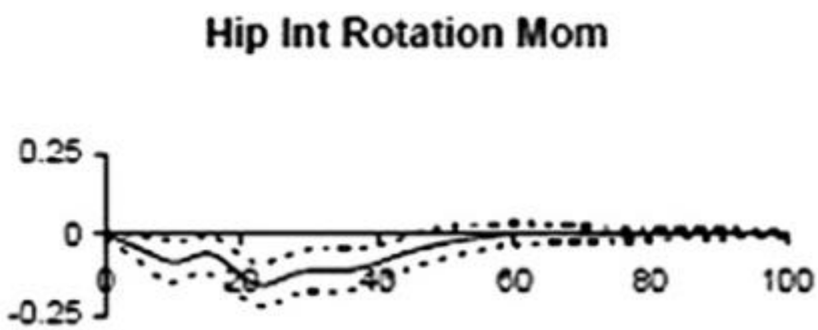

Figure 2.2.4.4.3 Applied hip internal rotation moment in the transverse plane. The x-axis is in percent of stance and y-axis is in (N-m)/kg. From Dicharry, J. with permission [31].

2.3 MEASUREMENT OF RUNNING BIOMECHANICS

2.3.1 MOTION ANALYSIS

The gold standard for motion analysis is a three-dimensional (3D), marker-based camera system. Motion capture systems use active, electromagnetic, or passive markers placed on anatomical landmarks to record each marker's 3D location in space. Models define how the markers link together to make segments. Motion between segments defines joint kinematics. Active markers emit light, EM markers detect the positions of the segments relative to a fixed transmitter, and passive markers reflect light [14, 60]. Motion capture systems are used clinically to quantify human motion. This information can be used for surgical assessment, physical therapy, and rehabilitation.

Motion analysis has been used in researching therapies for children with cerebral palsy (CP) [61]. Surgical procedures were adjusted in 89% of patients who underwent preoperative motion analysis and were reduced in 52% of the cases for children with CP [62, 63]. Motion analysis is also a tool for diagnosing and rehabilitating neuromuscular disorders [61, 64, 65]. Table *2.3.1.1* summarizes running studies using 3D, marker-based motion capture systems.

Table 2.3.1.1 Studies using three-dimensional (3D), marker-based motion capture systems in running analysis. F = female participants, M = male participants, and NSF = navicular stress fracture.

Study	**Participants**	**Results**
Ferber, R. et al. [66]	40 runners (20 F, 20 M)	Female runners had greater hip coronal and transverse work, peak hip adduction, hip internal rotation, and knee abduction
Chumanov, E.S. et al. [67]	34 runners (17 F, 17 M)	Female runners had greater peak hip internal rotation and adduction
Sinclair, J. and P.J. Taylor [68]	40 runners (20 F, 20 M)	Female runners had higher peak ankle eversion and tibial internal rotation
Willy, R.W. and I.S. Davis [69]	14 male runners	Running in the minimalist shoe showed higher knee flexion and ankle dorsiflexion at initial contact
Milner, C.E. et al. [70]	40 runners (20 with history of TSF, 20 controls)	No significant differences in ankle and knee stiffnesses and knee flexion excursion
Becker, J. et al. [5]	14 runners (7 with NSF, 7 controls)	Injured feet of NSF runners had lower abduction and higher rearfoot eversion excursion and eversion velocity

Three-dimensional motion capture systems have been used to examine gender differences in recreational runners. Researchers have found female runners have greater coronal plane hip motion compared to male runners [66, 67]. It has also been reported that female runners have greater peak tibial IR and ankle eversion [68]. Results like these are important to understand since female runners are more prone to running injuries [67]. Kinematic differences in running shoe design and injury groups have also been analyzed with motion systems. One study was able to determine that wearing a minimalist shoe, as opposed to a non-minimalist shoe, required greater knee flexion and ankle DF at IC [69]. Researchers found no kinematic differences between runners with and without tibial stress fractures [70], while ankle kinematic differences were found between runners with and without navicular stress fractures [5]. Motion capture systems can measure joint and segment positions, velocities, accelerations, and excursions [5, 61, 66-70]. The advantages of motion systems include accuracy, real-time results, and large amounts of data. However, there are disadvantages in motion systems such as required lab space, data processing, and cost [14, 71].

2.3.2 FORCE MEASUREMENTS

To determine joint kinetics, GRFs are measured and used in inverse dynamic equations to calculate joint kinetics. Some instrumentation that is used to measure GRFs while running are force plates and instrumented force treadmills. The following sections summarize running studies using these forms of instrumentation for GRF measurement.

2.3.2.1 FORCE PLATES

In many research labs, GRFs are measured using force plates. They can be used to measure loading rates, impact forces, and braking and propulsive forces, which are important in running analysis [14]. Table 2.3.2.1.1 summarizes studies that used force plates in their running analysis.

Table 2.3.2.1.1 Studies using force plates in running analysis. F = female participants, M = male participants, F_s = sampling frequency, PF = plantar flexion, LR = loading rate, and LE = lower extremity.

Study	Participants	Measurement Tools	Results
Greenhalgh, A. and Sinclair, J. [72]	30 runners (15 F, 15 M)	22-m indoor runway Kistler force plate (Kistler Instruments Ltd.; Alton, NH) F_s = 1000 Hz	Male runners had greater ankle PF moment and Achilles tendon load and LR
Orendurff, M.S. et al. [73]	12 runners (6 F, 6 M)	20-m indoor runway AMTI OR6-6 force plate (AMTI, Watertown, MA) F_s = 3000 Hz	Running speed had a significant effect on peak kinetics of the LE joints
Butler, R.J. et al. [74]	20 HA runners (11 F, 9 M) 20 LA runners (10 F, 10 M)	25-m indoor runway Bertec force plate (Bertec Corp.; Worthington, OH) F_s = 1080 Hz	Vertical LR was influenced by arch structure and shoe type
Sinclair, J. and Selfe, J. [75]	30 runners (15 F, 15 M)	Kistler force plate (Kistler Instrumente AG; Switzerland) F_s = 1000 Hz	Kinetic parameters for the knee were influenced by gender
Williams, D.S. III, et al. [76]	20 HA runners (10 F, 10 M) 20 LA runners (12 F, 8 M)	25-m indoor runway Bertec force plate F_s = 960 Hz	Arch structure influenced stiffness values, vertical LR, and spatiotemporal parameters

In running research, force plates are useful in measuring kinetic differences between high-arch and low-arch feet of runners [74, 76]. Low-arch structure influences lower leg stiffness, and increased stiffness and vertical loading rate associated with high-arched runners [76]. Force plates have also been used to examine gender differences in runners [72, 75]. Male runners have displayed greater Achilles tendon load and loading rate [72], but lower patellofemoral load and peak knee extensor moment [75]. Researchers determined that running speed had a significant influence on the peak kinetic values of the LE joints [73]. These studies are important in establishing risk factors in injuries such as Achilles tendinitis and patellofemoral pain. The disadvantages of using force plates are subject targeting, required lab space, cost, and discontinuous measurement [14].

2.3.2.2 FORCE TREADMILLS

Instrumented force treadmills are a common tool for running analysis. These treadmills are constructed with force plates embedded in the belt of the treadmill and allow for continuous GRF measurement under both feet [14, 51-53, 77]. Other advantages of instrumented treadmills include control of running speed and continuous walkway [77]. Table 2.3.2.2.1 summarizes studies that have used instrumented force treadmills in running analysis.

Table 2.3.2.2.1 Studies using instrumented force treadmills in running analysis. F = female participants, M = male participants, F_s = sampling frequency, GRF = ground reaction force, LR = loading rate, and FFS = forefoot striking.

Study	**Participants**	**Measurement Tools**	**Results**
Gerlach, K.E. et al. [78]	87 female runners (18-53 years)	Kistler force treadmill (Kistler Instrument Corp.; Amherst, NY) F_s = 520 Hz	Impact GRF and LR decreased post-exhaustive treadmill run

Study	Participants	Measurement Tools	Results
Knorz, S. et al. [79]	22 male runners (11 RFS, 11 FFS)	Split-belt force treadmill (Bertec Corp.; Worthington, OH) F_s = 1000 Hz	Strike patterns had significant influences on stress patterns, vertical GRF, and LR
Telhan, G. et al. [80]	19 runners (9 F, 10 M)	AMTI force treadmill (AMTI; Watertown, MA)	Significant differences were found in hip and knee powers and vertical GRF
Willson, J.D. et al. [81]	20 runners (10 F, 10 M)	Bertec force treadmill (Bertec Corp.; Columbus, OH) F_s = 2400 Hz	FFS runners had lower peak and overall patellofemoral force and stress

Instrumented treadmills were used in examining kinetic changes after an exhaustive treadmill run. The impact peak GRF and loading rate had a significant decrease after the treadmill run. Results showed kinetic changes were due to the muscle activation patterns of the ankle DF and invertor muscles [78]. Kinetic differences in striking patterns are also analyzed with instrumented treadmills [79, 81]. Runners with a history of ankle or hip injuries may benefit from a RFS pattern. Researchers showed lower shear stress in the ankle and hip joints in runners with a RFS pattern compared to a FFS pattern [79, 81]. Forefoot striking runners tend to have lower patellofemoral kinetics, especially if there is a history of knee injuries. These treadmills are also useful in analyzing the influence of the treadmill slope on running kinetics [80]. Prior research has found decreased kinetics during level running compared to incline running [82]. This is beneficial for runners who use incline and decline slope training to improve overall strength and cardiovascular health [80, 83].

2.3.3 OVERGROUND VERSUS TREADMILL RUNNING

Overground running is the typical running environment for most recreational runners. However, it is not ideal for motion analysis because a capture volume is required and there is no control of the environment. Treadmills are often used for running analysis because the capture volume can be easily calibrated and multiple, successive foot strikes can be recorded [84]. Because of this, studies have been done to determine if running dynamics during overground running are similar to running dynamics during treadmill running. Table 2.3.3.1 summarizes studies comparing running dynamics of overground and treadmill running.

Table 2.3.3.1 Studies comparing kinetics and kinematics between overground and treadmill running. F = female participants, M = male participants, F_s = sampling frequency, LE = lower extremity, GRF = ground reaction force, and LR = loading rate.

Study	**Participants**	**Measurement Tools**	**Results**
Sinclair, J. et al. [85]	12 runners (1 F, 11 M)	22-m indoor runway (Altro Ltd; Letchworth Garden City, Hertfordshire) Woodway treadmill (ELG; Weil Rhein, Germany)	Overground running showed higher values for peak knee and hip flexion, ankle inversion, and ankle eversion excursion
Hong, Y. et al. [10]	16 male amateur runners (22.9 ± 1.8 years)	30-m indoor runway Sportsart treadmill (Sportsart Fitness, USA) Pedar pressure insoles (Novel, Munich, Germany) F_s = 100 Hz for the insoles	Treadmill running had lower peak plantar pressures, contact times, and vertical GRF in the toe regions
Riley, P.O. et al. [86]	20 runners (10 F, 10 M)	15-m indoor runway Treadmill instrumented with AMTI force plate (AMTI, Watertown, MA)	Treadmill running had lower peak knee flexion and extension

Study	Participants	Measurement Tools	Results
Fellin, R.E. et al. [84]	20 runners (10 F, 10 M)	25-m indoor runway Quinton treadmill (Quinton Cardiology Inc.; Bothell, WA)	Kinematic curves were similar for the LE joints
Chambon, N. et al. [87]	12 male runners (21.8 ± 2.0 years)	Kistler force plate (Kistler Instrument Corp.; Amherst, NY) Force treadmill (Techmachine Medical Development®) 15-m indoor runway F_s = 2000 Hz (force plate and treadmill force sensors)	Shoe drop condition had significant effects on vertical GRF and LR
Schache, A.G. et al. [88]	10 runners (1 F, 9 M)	Force treadmill (Sportech Gymnasium and Electronic Sports; Australia) 40-m indoor, synthetic runway	Overground running had greater stride time, stride length, and swing time and lower stance time

While Fellin et al. found no significant differences between overground and treadmill running [84], other studies have shown decreased maximum hip flexion, decreased sagittal plane knee ROM, and reduced ankle ROM in treadmill running compared to overground [85-88]. When examining spatiotemporal parameters, researchers found that overground running had lower cadence and greater stride time and stride length compared to treadmill running [86, 88]. In the kinetic analysis, treadmill running has significantly lower plantar pressure and GRF compared to overground running [10]. These differences can be attributed to the cushioning of the running surface, since treadmill surfaces are often more compliant [89]. Overground and treadmill running analysis is also useful in understanding the effects of shoe heel heights [87].

2.3.4 PLANTAR PRESSURE MEASUREMENTS

Plantar pressure is an important factor to analyze as it is related to running injuries [90, 91]. Measuring plantar pressures during running helps in understanding how the tissues absorb forces to reduce shock to the body. This information is useful in investigating Achilles tendon loading characteristics of different striking patterns [92, 93]. High forces are experienced during mid-to-late stance of running and, over time, these tissues can be over-stretched and become injured. Common running injuries include shin splints, plantar fasciitis, tibial and foot stress fractures, and iliotibial band syndrome [15, 27, 28]. Plantar pressure analysis can determine what biomechanical factors are injury risk factors. This type of analysis can be measured by plates, insoles, force-sensing resistors, and treadmills [44, 94-96]. The following sections detail studies using pressure insoles and plates for kinetic analysis.

2.3.4.1 PRESSURE INSOLES

Pressure insoles allow for direct measurement of plantar pressure because they are worn between the runner's sock and shoe liner. They are advantageous for research clinics because they are flexible, portable, and can be used outdoors [95, 97, 98]. However, these devices have a limitation of not calculating shear forces. These forces contribute to braking and propulsive forces during running and are important in considering causes of running injuries. There is also a potential for sensors to slip during data collection [95]. Table 2.3.4.1.1 summarizes running studies using pressure insoles.

Table 2.3.4.1.1 Studies using pressure insoles to analyze plantar pressure in running analysis. F = female participants, M = male participants, F_s = sampling frequency, GRF = ground reaction force, LR = loading rate, and MSF = metatarsal stress fractures.

Study	**Participants**	**Measurement Tools**	**Results**
Barnett, S. et al. [4]	5 runners (2 F, 3 M; 25-41 years)	Pedar pressure insoles (Novel GmBH; Munich, Germany) Kistler force plate (Kistler Instrument Corp.; Amherst, NY) F_s = 99 Hz for both devices	Largest difference between devices was found in force data
Dixon, S.J. [8]	9 female runners	Footscan® pressure insoles (RScan International; Olen, Belgium) F_s = 500 Hz	Peak acceleration and force data showed differences in the shoe types
Kernozek, T.W. and Zimmer, K.A. [99]	17 college-aged students (24.58 ± 4.70 years)	Pedar pressure insoles F_s = 150 Hz	Increases in running speed led to increased plantar pressure and GRF as well as decreased pressure and force impulses
Low, D.C. and Dixon, S.J. [100]	8 runners (4 F, 4 M)	Footscan® pressure insoles AMTI force plate (AMTI, Watertown, MA)	Force plate had greater peak vertical GRF compared to pressure insoles
Mei, Q. et al. [12]	38 M runners (18 unshod, 20 shod)	10-m indoor runway Pedar pressure insoles Kistler force plate F_s = 1000 Hz for the force plate	Habitual shod runners had a greater vertical LR when running barefoot
Queen, R.M. et al. [101]	39 runners (15 M controls, 15 F controls, 9 F with history of MSF)	10-m indoor runway Pedar-X pressure insoles F_s = 100 Hz	Female controls had greater peak GRF in central forefoot compared to male controls and females with history of MSF
Ribeiro, A.P. et al. [102]	105 runners (60 controls, 45 with unilateral plantar fasciitis)	Pedar-X pressure insoles F_s = 100 Hz	No significant differences were found between injury and control groups

Studies using pressure insoles have involved comparing force measurements between force plates and pressure insoles [4, 100]. Disparity in force measurements between these devices may be attributed to design. Force plates have 3D sensors in each corner of the plate, so the recorded GRF is a resultant force of the entire plate. Pressure insoles can measure pressure in multiple regions of the foot and force is calculated using Equation 1:

$$F = P * A \tag{1}$$

Where F = force, P = pressure, and A = area of contact [90]. Pressure insoles are useful in determining influence of running speed, running shoes, and striking pattern on loading in different regions of the foot [8, 12, 99]. These devices have been used in analyzing pressure metrics for running injuries, which is useful in injury treatment and prevention [101, 102].

2.3.4.2 PRESSURE PLATES

Pressure plates are forms of instrumentation to measure plantar pressure during walking and running. These devices directly measure COP, which is useful in determining whether an injury can be associated with a specific region of the foot or progress made in physical therapy [90, 91]. Table 2.3.4.2.1 summarizes studies using pressure plates in running analysis.

Table 2.3.4.2.1 Studies using pressure plates to measure plantar pressure in running analysis. F = female participants, M = male participants, F_s = sampling frequency, COP = center of pressure, ITBS = iliotibial band syndrome, and GRF = ground reaction force.

Study	**Participants**	**Measurement Tools**	**Results**
Breine, B. et al. [103]	55 runners (15 F, 40 M)	AMTI force plate (AMTI; Watertown, MA) Footscan® pressure plate (RScan International; Olen, Belgium) F_s = 1000 Hz (force plate) F_s = 500 Hz (pressure plate)	Runners contacted the ground more anteriorly when running speed increased
Morrison, K.E. et al. [104]	45 runners (27 F, 18 M)	19-m indoor runway Tekscan® pressure mat (Tekscan Inc.; Boston, MA) F_s = 66 Hz	Runners with chronic ankle instability had a more rearfoot lateral COP trajectory and pressure distribution
Willems, T.M. et al. [105]	400 physical education students (159 F, 241 M)	16.5-m wooden running track Footscan® pressure plate F_s = 480 Hz	Risk factors for exercise-related lower leg pain were determined
Nagel, A. et al. [106]	200 marathon runners (33 F, 167 M)	EVA foam runway Emed ST-2 and ST-4 pressure platforms (Novel GmBH; Munich, Germany) F_s = 50 Hz	Peak plantar pressure and force impulse increased in metatarsal 2-5, great toe, and lesser toes post-marathon
Thijs, Y. et al. [107]	129 runners (107 F, 22 M)	15-m indoor runway Footscan pressure plate F_s = 480 Hz	Pre-disposing risk factors for patellofemoral pain were determined
Van Ginckel, A. et al. [108]	129 runners (110 F, 19 M)	15-m indoor runway Footscan pressure plate F_s = 480 Hz	Risk factors for Achilles tendinopathy were determined for novice runners
Grau, S. et al. [109]	18 runners with ITBS (5 F, 13 M) 54 controls (18 in 3 groups)	15-m indoor, EVA foam runway Emed-X pressure plate (Novel GmBH; Munich, Germany) F_s = 100 Hz	ITBS runners had lower peak medial forefoot GRF and greater rearfoot force impulse compared to group 1 runners

Pressure plates have been used to measure foot contact patterns and how it is affected by changes in running speed during distance running [103, 106, 110]. These devices are useful in measuring how COP patterns change with different pathologies such as patellofemoral pain, plantar fasciitis, iliotibial band syndrome, Achilles tendinitis, and metatarsal stress fractures [91, 104, 105, 107-109]. Important metrics related to running injuries that can be measured by pressure plates are contact time, plantar pressure, contact area, and locations of plantar pressure and GRF [91]. The advantages of using a pressure plate are that they are stationary, flat, and easy-to-use. Limitations of a pressure plate are requirement of dedicated lab space and subject targeting the plate [95, 96].

CHAPTER 3: MATERIALS AND METHODS

3.1 SUBJECT POPULATION

The Froedtert/Medical College of Wisconsin's (MCW) Institutional Review Board approved the protocol, recruitment flyers, and consent forms for this study. The study was conducted at the MCW Department of Orthopaedic Surgery's Center for Motion Analysis. Participants were recruited from publicity posted flyers. Eligibility criteria for the participants included: at least 18 years old, run at least 10 miles per week, have no history of cardiovascular disease, have at least a moderate comfort level with treadmill running, and have no current lower body injuries. A moderate comfort level was defined as ranking a 5 or higher on a scale of 0-10, with 0 being totally uncomfortable and 10 being extremely comfortable.

Before the testing session began, each participant was given explanations about the testing session and gave written informed consent. There were eleven male participants with an average age of 31.4 ± 11.5 years, height of 1824.5 ± 56.5 mm, body mass of 80.3 ± 11.2 kg, and running speed of 7.1 ± 1.1 mph. Fifteen females participated in the study with an average age of 30.2 ± 7.0 years, height of 1738.2 ± 75.6 mm, body mass of 65.1 ± 11.6 kg, and running speed of 6.1 ± 0.7 mph. The foot strike pattern of each runner was determined from plantar pressure data. These files contained timing of IC for each foot region, and then percent of IC was compared between the regions. All participants in the study were RFS runners.

3.2 TESTING SESSION

At the beginning of the testing session, anthropometric measurements were taken of the participant as inputs into Vicon's Nexus software for their lower body Plug-in Gait (PiG) model (Vicon Motion Systems, Ltd.; Oxford, UK). Measurements were taken of height, body mass, inter anterior-superior iliac spine (ASIS) distance, leg lengths, and ankle and knee widths. Fifteen markers were placed on the participant's pelvis and lower limbs and a Polar heart rate monitor (Polar Electro, Inc.; Bethpage, NY) was placed around their chest.

The anatomical landmarks for the lower body PiG model markers were the left and right ASIS, posterior sacrum midway between the left and right posterior-superior iliac spines (PSIS), left and right patellas, left and right lateral femoral epicondyles, left and right lateral shanks, left and right lateral malleoli, left and right medial malleoli, left and right heels of the running shoe at the height of the calcaneal tuberosities, and on the left and right second metatarsal heads, on the running shoes, at the same height as the calcaneal tuberosities.

A knee-alignment device (KAD) was put on both knees to determine the knee joint centers and tibial rotation in the static model. The KADs and medial malleolus markers were removed and markers were placed on both lateral femoral epicondyles for the dynamic trials [111].

3.2.1 MOTION ANALYSIS ASSESSMENT

A 12-camera Vicon MX motion capture system (Vicon Motion Systems, Ltd.; Oxford, UK) was used to collect marker position data at a sampling frequency of 150 Hz. Fifteen markers were used to define seven segments to collect the joint kinematics. The left anterior-superior iliac spine (LASI), right anterior-superior iliac spine (RASI), and posterior sacrum (SACR) markers defined the pelvis segment. For each side, the thigh segment was defined by the ASI, thigh (THI), and knee (KNE) markers, the shank segment was defined by the KNE, tibia (TIB), and ankle (ANK) markers, and the foot was defined by the ANK, heel (HEE), and TOE markers. **Error! Reference source not found.** lists the markers that defined each segment and the anatomical landmarks and Figure *3.2.1.1* shows the marker set-up for the seven segments in Nexus.

Table 3.2.1.1 Definition of segments used in the lower body Plug-in Gait model in Nexus based on markers and anatomical landmarks. L = left side, R = side, ASI = markers for anterior-superior iliac spines (ASIS), SACR = posterior sacrum marker, THI = thigh markers, KNE = knee markers, TIB = tibial markers, ANK = ankle markers, HEE = heel markers, TOE = toe markers, and PSIS = posterior-superior iliac spine.

Segment	**Markers**	**Anatomical landmarks**
Pelvis	LASI RASI SACR	Left ASIS Right ASIS Posterior sacrum midway between left and right PSIS
Left thigh	LASI LTHI LKNE	Left ASIS Left patella Left lateral femoral epicondyle
Left shank	LKNE LTIB LANK	Left lateral femoral epicondyle Left lateral shank Left lateral malleolus
Left foot	LANK LHEE LTOE	Left lateral malleolus Left calcaneal tuberosity Left 2nd metatarsal head
Right thigh	RASI RTHI RKNE	Right ASIS Right patella Right lateral femoral epicondyle

Segment	Markers	Anatomical landmarks
Right shank	RKNE RTIB RANK	Right lateral femoral epicondyle Right lateral shank Right lateral malleolus
Right foot	RANK RHEE RTOE	Right lateral malleolus Right calcaneal tuberosity Right 2nd metatarsal head

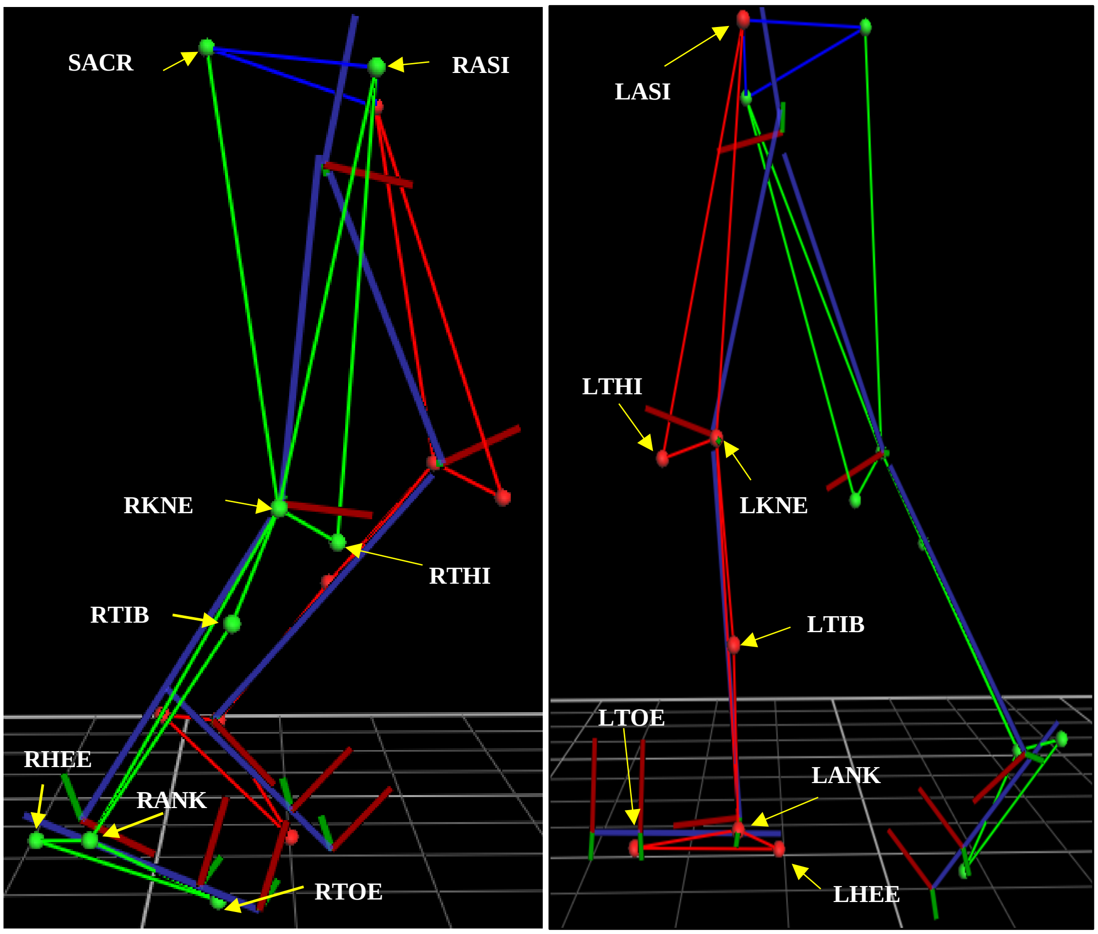

Figure 3.2.1.1 Lateral views of marker set-up in Nexus. Red signifies the left side (L) and green signifies the right side (R). The ASI markers represent the anterior-superior iliac spines (ASIS), SACR marker represents the posterior sacrum, THI markers represent the left and right thighs, KNE markers represent left and right knees, TIB markers represent left and right shanks, ANK markers represent left and right ankles, HEE markers represent left and right heels, and TOE markers represent left and right toes.

The foot progression angle was defined as the rotations of the foot relative to the vertical axis in the global coordinate system of the lab. Segmental kinematic angles were measured relative to the nearest proximal segment. The pelvis angles were measured relative to the global coordinate system of the lab.

3.2.2 PLANTAR PRESSURE ASSESSMENT

The Quasar pressure treadmill (Noraxon USA, Inc.; Scottsdale, AZ) has 10,240 pressure sensors (170 cm by 65 cm) and records at a sampling frequency of 300 Hz. This treadmill was hard-wired synced with the Vicon motion system by sending a 5 V pulse to the myoPRESSURE software when motion recording started until motion recording was stopped. Participants warmed up until a comfortable speed was reached and their heart rate (HR) was within 70-80% of the maximum HR, as calculated by Equation 2:

$$HR_{max} = 220 - age \tag{2}$$

Ten trials with six strides each were collected from each participant. Each treadmill session lasted between 15 and 20 minutes. The data points of left and right vertical GRFs and plantar pressure were exported from the myoPRESSURE program of the MyoResearch software package to an Excel workbook for input into Matlab (Mathworks, Inc.; Natick, MA).

3.3 DATA PROCESSING

To measure the joint kinematics, the markers, foot strike, and foot off events for two strides were manually labeled. Each trial was then run through a data processing pipeline in Nexus that deleted unlabeled trajectories, autocorrelated stride events for the trial, applied a Woltring filter with a mean square error value of 10, processed the PiG model, filtered model outputs with a low-pass Butterworth filter with a cut-off frequency of 10 Hz, calculated gait cycle parameters (cadence, running speed, stride time, step time, time of double support, stride length, and step length), and exported the data to .c3d and .csv files. The .csv files of the joint kinematics and treadmill data were converted to Excel workbooks for Matlab implementation.

To determine the foot strike patterns, plantar pressure data, which contained timing of IC for each foot region, was first examined by comparing percent of IC between the regions. Then, sagittal plane ankle angles were also looked at to confirm the strike pattern. The foot strike pattern was also visually confirmed in Nexus by whether or not the runner was rearfoot striking.

Before data was processed in Matlab, data from three participants were excluded from the study. Two female participants ran below 5 mph, which is below the threshold for what is considered running on a treadmill [112]. One male participant was excluded because the running speed was greater than two standard deviations above the population average for the males and joint kinematics are influenced by running speed [73]. The data presented in the results are of the participants included in the final analysis.

Joint kinematics, GRFs, and plantar pressures were extracted during stride events that were identified in Vicon. Stance phase was defined by plantar pressure exceeding 0 N/cm^2 and swing phase was defined when plantar pressure was 0 N/cm^2. The treadmill data was down sampled to 150 Hz in Matlab to match that of the Vicon system. The downsample Matlab function decreased the sampling rate of the treadmill data by a factor of two. Once treadmill data was down sampled, the synced GRF, plantar pressures, and joint angles were extracted and parameters of interest were calculated during stance phase.

The parameters of interest for joint kinematics were the sagittal and coronal plane motion of the ankle and hip and sagittal plane motion of the knee. Important parameters for plantar pressure are peak plantar pressure, peak GRF, force impulse, and pressure impulse. Peak GRF and plantar pressure for the entire foot was determined in Matlab using the max function on the plantar pressure data. Force and pressure impulses were calculated using the trapz function in Matlab, which performed the integral of the force-time and pressure-time curves. Peak GRF and force impulse data for the foot in three and ten zones were extracted from .xlsx files. These parameters were chosen based on a systematic review of running studies examining plantar pressure measurements and running-related injury [91]. The peak GRF and force impulse were determined for the entire foot, as well as three and ten zones of the foot as defined in the myoPRESSURE software (Figure 3.3.1).

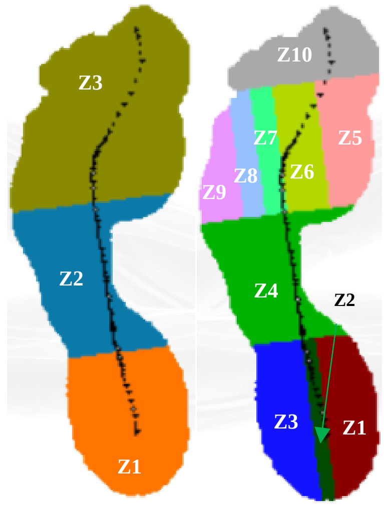

Figure 3.3.1 Three zones (left) and ten zones (right) of the foot. The regions when the foot is divided into three zones are the hindfoot (Z1), midfoot (Z2), and forefoot (Z3). When the foot is divided into ten zones, those regions are the medial hindfoot (Z1), central hindfoot (Z2), lateral hindfoot (Z3), midfoot (Z4), metatarsals 1-5 (Z5-Z9), and toes (Z10). Adapted from the Noraxon myoPRESSURE software guide [113].

3.4 STATISTICAL ANALYSIS

Minitab® 18 (Minitab, LLC; State College, PA) was used to perform the statistical analysis for this study. The Ryan-Joiner test, like the Shapiro-Wilk test, was done with a p-value of 0.05 to determine if the subject data comes from a normally distributed population. Results of the Ryan-Joiner test showed the data was not normally distributed (non-parametric data), so the Spearman rho correlation test, also with a p-value of 0.05, was used to test the hypothesis.

Six correlation tests were performed to test the hypothesis. The first test examined peak GRF and plantar pressure for the entire foot versus kinematics at the same time points. The second test examined peak kinematics against GRF and plantar pressure at the same time points. For the third and fourth tests, peak GRF for the three zones and ten zones, respectively, were tested against the kinematic parameters at the time points of the peak GRF. In the fifth and sixth tests, speed was examined against peak GRF and peak plantar pressure data, respectively. The Mann-Whitney U test, with a p-value of 0.05, was also performed to determine significant differences in the plantar pressure and kinematic metrics between female and male participants.

CHAPTER 4: RESULTS

4.1 SPATIO-TEMPORAL PARAMETERS

Fifteen females (age 30.2 ± 7.0 years, height 1738.2 ± 75.6 mm, body mass 65.1 ± 11.6 kg) and eleven males (age 31.4 ± 11.5 years, height 1824.5 ± 56.5 mm, body mass 80.3 ± 11.2 kg) participated in the study. Male participants had significantly greater body mass, were significantly taller, and were significantly older ($p < 0.05$) than the female participants.

The calculated spatio-temporal parameters for this study were running speed, stance time, and cadence. Running speed was recorded from the treadmill, to one decimal place, at the time when a participant's heart rate (HR) was within 70-80% of the maximum, as calculated by Equation 2. Stance time was calculated by dividing the number of frames in a stance phase by the sampling frequency, which was 150 Hz. The stance percentages were compared with the treadmill data and previous studies to determine if the percentages matched previously reported data. Cadence was measured by the Vicon system and extracted from the .csv files. Table *4.1.1* lists the group averages and standard deviations for the spatio-temporal parameters. There were no statistical differences between the participant groups for the spatio-temporal parameters.

Table 4.1.1 Group averages of spatio-temporal parameters for the study. Running speed was measured in miles per hour (mph), stance time is in seconds (s), and cadence is in steps per min (steps/min). Data is presented as mean (± 1 standard deviation).

	Females	**Males**	**p-values**
Running Speed (mph)	6.1 (0.71)	7.1 (1.09)	0.190
Stance Time (s)	0.29 (0.03)	0.27 (0.03)	0.062
Cadence (steps/min)	167 (9.82)	167 (6.39)	0.836

4.2 JOINT KINEMATICS

Joint kinematics were extracted during stance phase, which was identified from the pressure data. The kinematics were normalized to 101 points, representing 0-100% of stance. Peak values (Table *4.2.1*) for female and male groups were used in the correlation tests. Kinematic parameters examined for this study were sagittal and coronal plane motion of the ankle and hip and sagittal plane motion for the knee.

Females had significantly greater sagittal plane ankle ROM compared to males (

Figure 4.2.1). While there were no statistically significant differences in peak ankle DF, females trended towards a higher peak ankle DF. In the coronal plane, females also showed significantly greater ankle ROM (

Figure *4.2.2*). Females trended towards a greater peak ankle inversion (7.2°) compared to males (4.8°). At the knee, males exhibited significantly greater knee flexion compared to females (

Figure *4.2.3*). The male participants experienced peak knee flexion at 38.6% of stance whereas females reached a peak knee flexion at 37.5% of stance.

Hip motion in the sagittal plane was the only kinematic parameter that did not show a statistically significant difference between females and males (

Figure *4.2.4*). However, females trended towards a greater hip flexion at IC (28.5°) compared to males (22.6°). In the coronal plane, females displayed significantly greater ROM for the hip during stance (Figure 4.2.5). Although not significant, females exhibited greater peak hip ADD than males (Table *4.2.1*).

Table 4.2.1 Peak joint kinematics for the study. The peaks were determined during the stance phase. Data is presented as mean (± 1 standard deviation). DF = Dorsiflexion.

	Females	**Males**	**p-values**
Peak Ankle DF (°)	25.5 (12.5)	17.1 (8.1)	0.078
Peak Knee Flexion (°)	34.6 (9.7)	42.4 (6.9)	0.087
Peak Hip Flexion (°)	28.5 (15.4)	22.6 (10.4)	0.533
Peak Ankle Inversion (°)	7.2 (2.4)	4.8 (1.6)	0.194
Peak Hip Adduction (°)	10.0 (4.3)	6.4 (3.3)	0.324

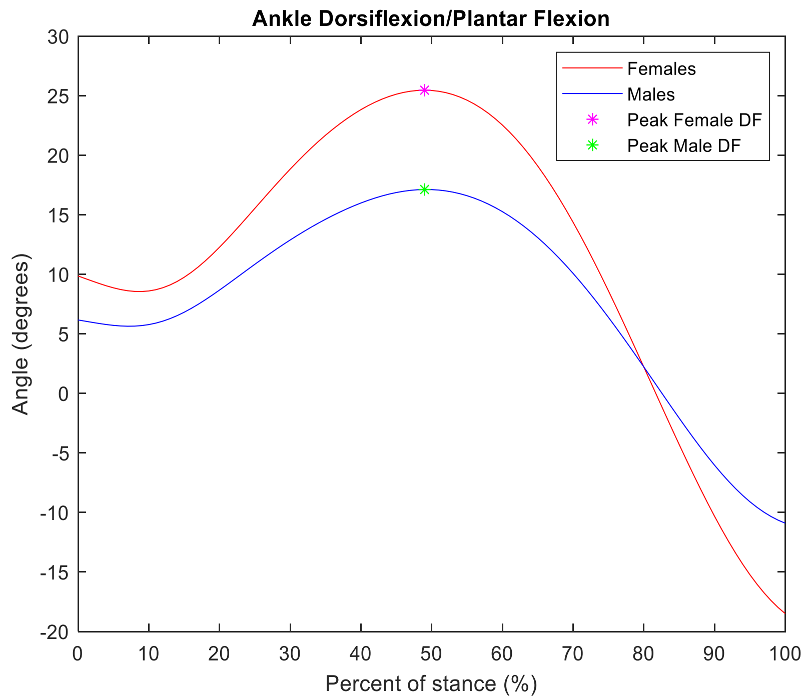

Figure 4.2.1 Sagittal plane ankle kinematics during stance. Dorsiflexion (DF) is positive (+) and plantar flexion (PF) is negative (-).

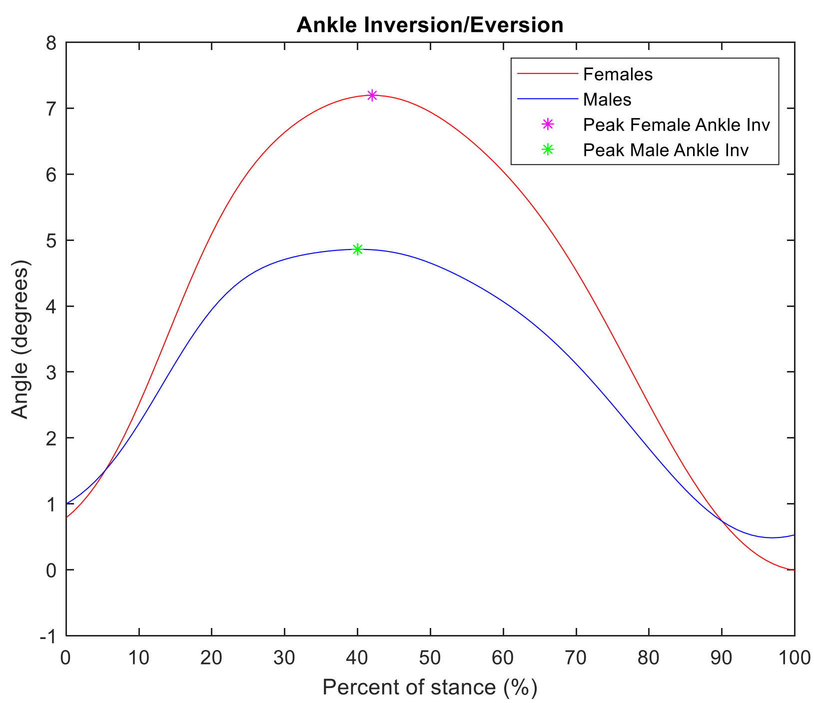

Figure 4.2.2 Coronal plane ankle kinematics during stance. Inversion is positive (+) and eversion is negative (-).

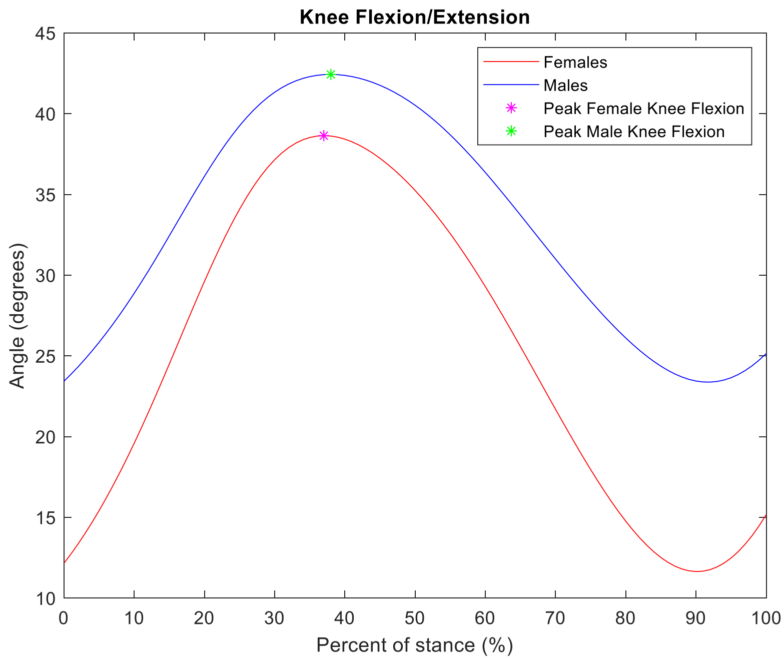

Figure 4.2.3 Sagittal plane knee kinematics during stance. Flexion is positive (+) and extension is negative (-).

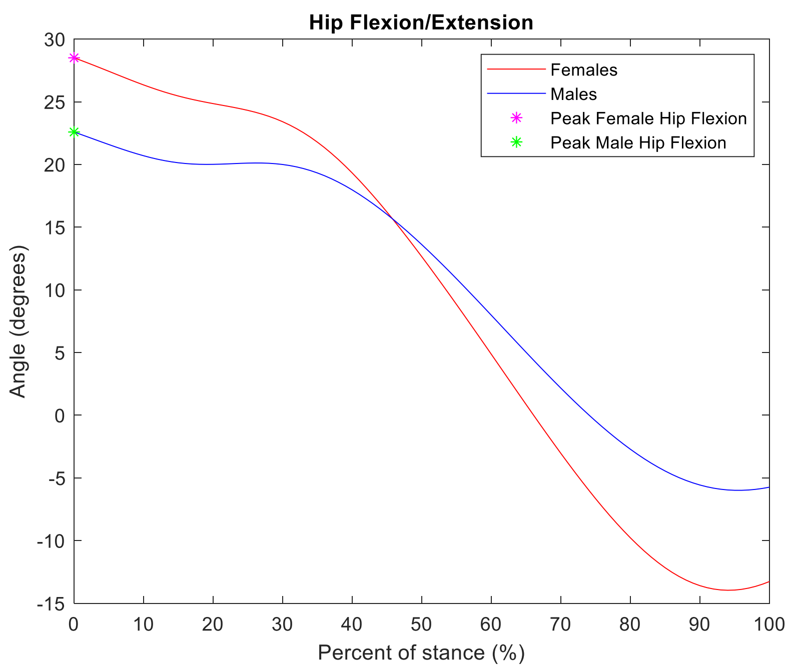

Figure 4.2.4 Sagittal plane hip kinematics during stance. Flexion is positive (+) and extension is negative (-).

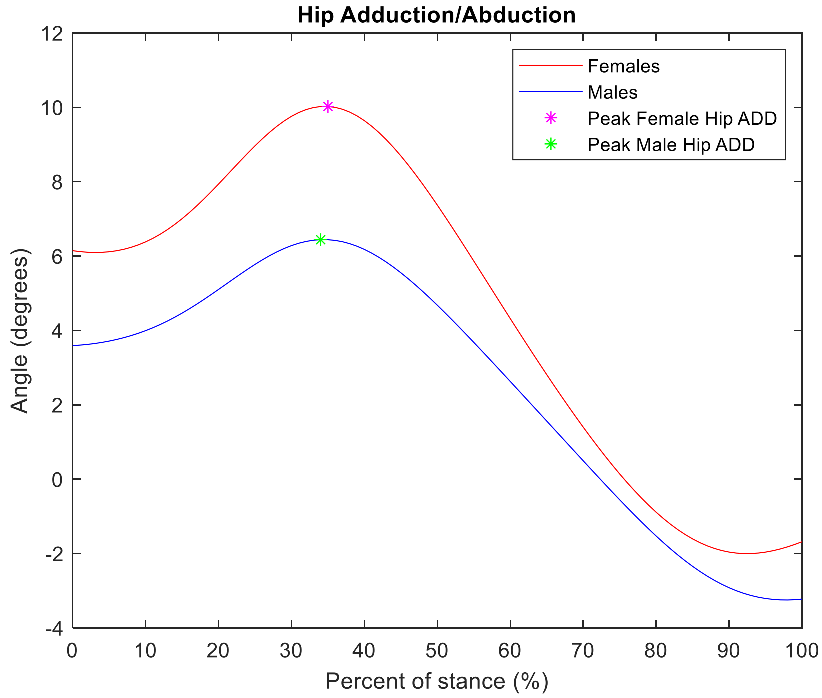

Figure 4.2.5 Coronal plane hip kinematics during stance. Adduction (ADD) is positive (+) and abduction (ABD) is negative.

4.3 PLANTAR PRESSURE METRICS

The plantar pressure metrics examined in this study were peak plantar pressure and pressure impulse for the entire foot, peak GRF and force impulse for the entire foot and when the foot was divided into three zones and ten zones.

There were no statistical differences in peak GRF and force impulse data between the participant groups. Statistically significant differences were seen in peak plantar pressure and pressure impulse data (Table *4.3.1*). Females had significantly greater peak plantar pressure and pressure impulse compared to males.

Figure *4.3.1* and

Figure *4.3.2* show group averages of the vertical GRF and plantar pressure during stance phase.

Table 4.3.1 Plantar pressure metrics for the entire foot. GRF = Ground reaction force and PP = Plantar pressure. GRF is measured in BW, force impulse is measured in BW-s, PP is measured in kPa/kg, and pressure impulse is measured in (kPa-s)/kg. Data is presented as mean (± 1 standard deviation). The asterisk (*) indicates a significant difference between participant groups.

	Females	**Males**	**p-values**
Peak GRF (BW)	1.77 (0.03)	1.88 (0.03)	0.194
Force Impulse (BW-s)	0.69 (0.06)	0.73 (0.08)	0.350
***Peak PP (kPa/kg)**	**2.84 (0.77)**	**2.42 (0.65)**	**0.043**
***Pressure Impulse ((kPa-s)/kg)**	**1.37 (0.27)**	**1.10 (0.21)**	**0.013**

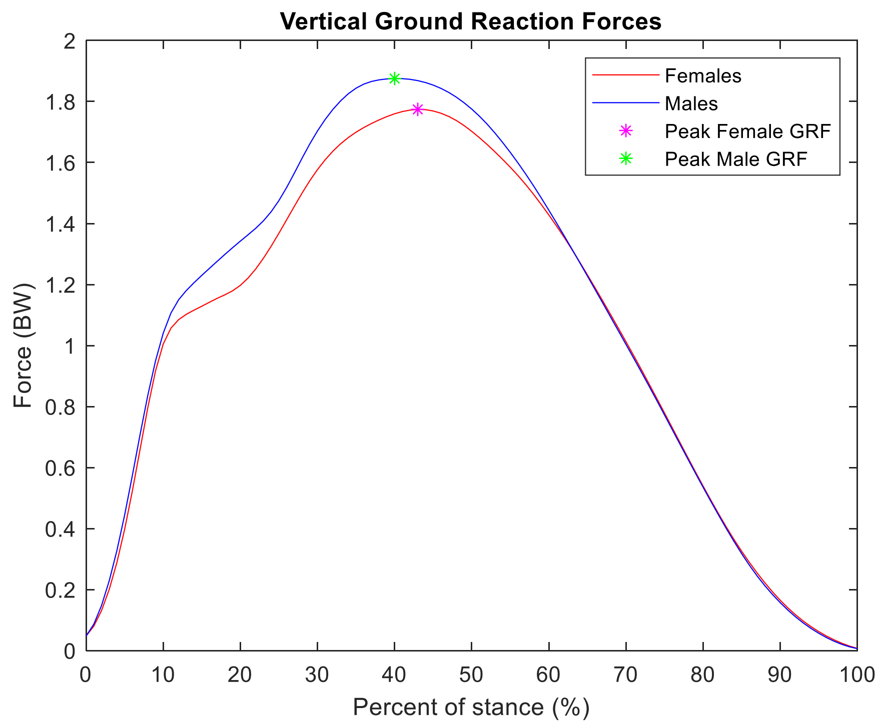

Figure 4.3.1 Vertical ground reaction forces (GRFs) during the stance phase.

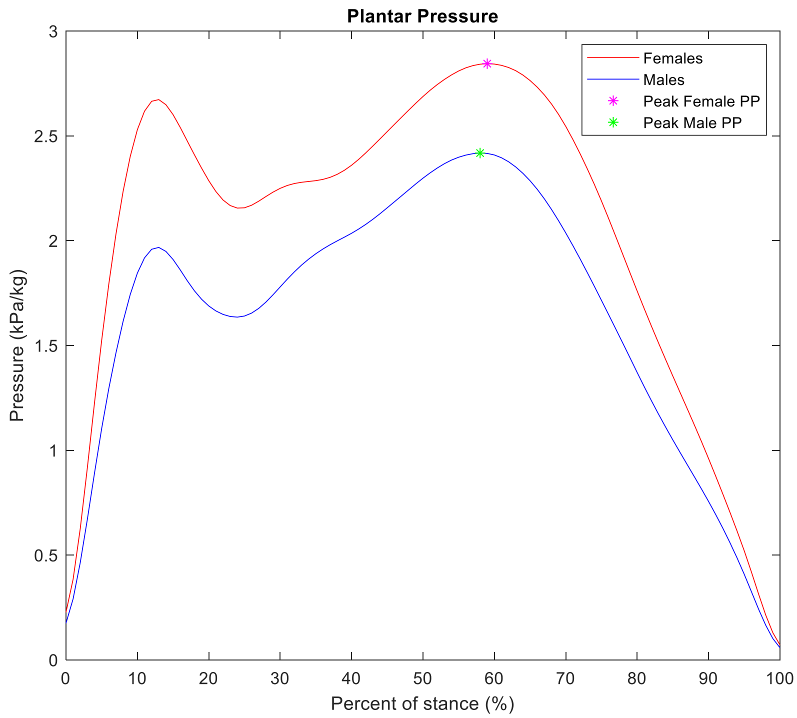

Figure 4.3.2 Plantar pressure during the stance phase.

Plantar pressure metrics were assessed with the foot divided into three (Table *4.3.2*) and ten zones (Table *4.3.3*). There were no statistical differences in peak HF and FF GRFs when the foot was divided into three zones. However, the peak MF GRF was significantly greater in males (74% BW vs 62% BW). This difference was also seen when the foot was divided into ten zones (62% BW for males vs 50% BW for females).

Table 4.3.2 Peak ground reaction force (GRF) when the foot is divided into three zones. Those zones are hindfoot (HF), midfoot (MF), and forefoot (FF) and the units are in body weight (BW). Data is presented as mean (± 1 standard deviation). The asterisk (*) indicates a significant difference between participant groups.

	Females	**Males**	**p-values**
Peak HF (BW)	0.72 (0.10)	0.61 (0.20)	0.119
***Peak MF (BW)**	**0.62 (0.09)**	**0.74 (0.11)**	**0.015**
Peak FF (BW)	1.38 (0.19)	1.44 (0.19)	0.604

Table 4.3.3 Peak ground reaction force (GRF) when the foot is divided into ten zones. Those zones are the medial heel (HM), central heel (HC), lateral heel (HL), midfoot (MF), metatarsals 1-5 (M1-M5), and toes (T). The GRF units are in body weight (BW). Data is presented as mean (± 1 standard deviation). The asterisk (*) indicates a significant difference between participant groups.

	Females	**Males**	**p-values**
Peak HM (BW)	0.36 (0.06)	0.31 (0.09)	0.087
Peak HC (BW)	0.08 (0.03)	0.07 (0.04)	0.876
Peak HL (BW)	0.41 (0.07)	0.37 (0.11)	0.436
***Peak MF (BW)**	**0.50 (0.08)**	**0.62 (0.09)**	**0.006**
Peak M1 (BW)	0.31 (0.05)	0.34 (0.05)	0.350
Peak M2 (BW)	0.39 (0.06)	0.39 (0.07)	0.795
Peak M3 (BW)	0.18 (0.03)	0.18 (0.03)	0.795
Peak M4 (BW)	0.16 (0.03)	0.15 (0.03)	0.716
Peak M5 (BW)	0.13 (0.03)	0.13 (0.03)	1.000
Peak T (BW)	0.31 (0.07)	0.31 (0.07)	0.795

There were also significant differences in the MF force impulse when the foot was divided into three (Table *4.3.4*) and ten (Table *4.3.5*) zones. In both cases, males had a significantly greater force impulse in the midfoot compared to females.

Table 4.3.4 Force impulse data when the foot is divided into three zones. Those zones are the hindfoot (HF), midfoot (MF), and forefoot (FF). The units for force impulse are BW-s. Data is presented as mean (± 1 standard deviation). The asterisk (*) indicates a significant difference between participant groups.

	Females	**Males**	**p-values**
HF Force Impulse (BW-s)	0.09 (0.02)	0.07 (0.03)	0.097
***MF Force Impulse (BW-s)**	**0.15 (0.02)**	**0.19 (0.02)**	**0.004**
FF Force Impulse (BW-s)	0.44 (0.07)	0.46 (0.08)	0.755

Table 4.3.5 Force impulse data when the foot is divided into ten zones. Those zones are the medial heel (HM), central heel (HC), lateral heel (HL), midfoot (MF), metatarsals (M1-M5), and toes. The units for force impulse are BW-s. Data is presented as mean (± 1 standard deviation). The asterisk (*) indicates a significant difference between participant groups.

	Females	**Males**	**p-values**
HM Force Impulse (BW-s)	0.05 (0.01)	0.04 (0.02)	0.062
HC Force Impulse (BW-s)	0.01 (0.003)	0.01 (0.005)	1.000
HL Force Impulse (BW-s)	0.05 (0.02)	0.04 (0.02)	0.324
***MF Force Impulse (BW-s)**	**0.12 (0.02)**	**0.15 (0.02)**	**0.002**
M1 Force Impulse (BW-s)	0.10 (0.02)	0.11 (0.02)	0.254
M2 Force Impulse (BW-s)	0.13 (0.02)	0.13 (0.03)	0.959

	Females	Males	p-values
M3 Force Impulse (BW-s)	0.06 (0.01)	0.06 (0.01)	0.467
M4 Force Impulse (BW-s)	0.05 (0.01)	0.05 (0.01)	0.795
M5 Force Impulse (BW-s)	0.04 (0.009)	0.04 (0.008)	0.276
T Force Impulse (BW-s)	0.09 (0.02)	0.08 (0.02)	0.917

4.4 CORRELATION RESULTS

Six Spearman rho correlation tests were performed on both male and female groups (p-value = 0.05). Significant results will be discussed here; full statistical results can be found in Appendix A. The first test compared peak GRF and plantar pressure values to joint kinematics. This test showed that female participants had a statistically significant positive correlation between peak plantar pressure and ankle DF, knee flexion, and ankle inversion (Table *4.4.1*).

Table 4.4.1 Statistically significant correlations in the female population between peak plantar pressure and joint kinematics. R_s = correlation coefficient, p = p-value, and DF = Dorsiflexion.

Comparison	Correlation and Significance
Peak Plantar Pressure vs Ankle DF	$r_s = 0.867$ $p = 0.001$
Peak Plantar Pressure vs Knee Flexion	$r_s = 0.915$ $p = 0.000$
Peak Plantar Pressure vs Ankle Inversion	$r_s = 0.830$ $p = 0.003$

In the second test, peak joint kinematics were compared to GRF and plantar pressure values for the entire foot. While males had a statistically significant positive correlation between peak knee flexion and plantar pressure (Table *4.4.2*), it was only a moderate correlation. The third and fourth tests compared peak GRF for the foot in three and ten zones, respectively, to the joint kinematics (Table *4.4.2*). Male participants showed a statistically significant negative correlation between peak MF GRF and hip flexion when the foot was divided into three zones. Males demonstrated a positive correlation between peak M1 GRF and hip ADD. The male participants also showed a negative correlation between peak M3 GRF and ankle DF, peak M4 GRF and ankle DF, and peak M5 GRF and knee flexion.

Table 4.4.2 Statistically significant correlations in the male population from three tests: peak kinematics and plantar pressure, peak ground reaction force (GRF) in three zones and joint kinematics, and peak GRF in ten zones and joint kinematics. R_s = correlation coefficient, p = p-value, ADD = adduction, DF = dorsiflexion, MF = midfoot zone, M1 = 1st metatarsal, M3 = 3rd metatarsal, M4 = 4th metatarsal, and M5 = 5th metatarsal.

Comparison	Correlation and Significance
Peak Knee Flexion vs Plantar Pressure	$r_s = 0.467$ $p = 0.025$
Peak MF GRF vs Hip Flexion	$r_s = -0.750$ $p = 0.020$
Peak M1 GRF vs Hip Adduction	$r_s = 0.683$ $p = 0.042$
Peak M3 GRF vs Ankle DF	$r_s = -0.700$ $p = 0.036$
Peak M4 GRF vs Ankle DF	$r_s = -0.800$ $p = 0.010$
Peak M5 GRF vs Knee Flexion	$r_s = -0.717$ $p = 0.030$

In the last two correlation tests, speed was compared to peak GRF and plantar pressure data of the entire foot. Both groups had positive correlations between speed and peak plantar pressure, but the results were not statistically significant. Females showed a statistically significant positive correlation between speed and peak GRF for the entire foot (Table *4.4.3*). Males also had a positive correlation between speed and peak GRF but it was not statistically significant.

Table 4.4.3 Correlation tests comparing speed to peak ground reaction force (GRF) and plantar pressure (PP). R_s = correlation coefficient and p = p-value.

	Females	Males
Speed vs Peak GRF	$\mathbf{r_s = 0.533}$ $\mathbf{p = 0.041}$	$r_s = 0.405$ $p = 0.216$

	Females	**Males**
Speed vs Peak PP	$r_s = 0.118$ $p = 0.677$	$r_s = 0.501$ $p = 0.116$

CHAPTER 5: DISCUSSION

5.1 SPATIO-TEMPORAL PARAMETERS

While there were no significant statistical differences in running speed, males averaged lower stance time and higher running speed. The relationship between lower stance time and higher running speed has also been reported in previous studies [31, 53]. It has been reported males had a significantly higher running speed than females [114, 115]. In the Rueda et al. study, female runners also had shorter stride lengths and smaller stride length to height ratio [115]. The researchers suggest that it is because females had a significantly smaller hip extension at toe-off compared to males. This study did not find significant differences in sagittal plane hip motion, but females did have a smaller hip extension at toe-off.

There were no statistical differences in cadences, but females had a larger standard deviation than males. Turner et al. also found no gender differences in cadence in collegiate cross-country runners, but females also had a greater standard deviation compared to males [116]. The differences in cadence standard deviation may be attributed to cadence training, however it was not detailed in this study nor the Turner et al. study whether runners previously had cadence training. The goal is to run with the same cadence at any running speed, so the LE joints experience less loads. When cadence is increased, time spent in stance phase is reduced and less energy is absorbed [117, 118]. Participants in this study were within the ideal range for running cadence, which is between 170 and 180 steps per min [119].

5.2 JOINT KINEMATICS

The kinematic parameters of sagittal and coronal plane motion of the ankle and hip and sagittal plane motion of the knee during stance phase examined in this study were chosen based on a systematic review of running studies relating plantar pressure metrics to running injuries [91].

The differences seen in ankle DF and knee flexion may be associated with the different running speeds between males and females. While not statistically significant, males had a higher average running speed of 7.1 mph compared to 6.1 mph for females. During stance, there is an increased knee flexion and decreased ankle DF as running speed increases [31, 53, 56]. When the running speed is increased, concentric activity of the knee flexors is increased for the greater shock absorption required at IC. Activity of the ankle PF muscles will also increase to prevent tibial advancement over the foot and to generate power for propulsion into swing phase [120, 121].

Females also had a significantly higher coronal plane ankle motion in stance phase compared to the males; however, the difference in peak ankle inversion was not statistically significant. Peak values for females occurred later during the stance phase due to the females having a slightly longer stance time. Peak values for females occurred later during the stance phase due to the females having a slightly larger stance percentage of 42%, compared to 39% for males. This result is important because lateral ankle sprains are a common ankle injury in running [122], with females having a higher incidence than males [15, 123]. Risk factors for lateral ankle sprains include excessive inversion and IR and increased PF at IC [122, 124].

The results from this study of increased hip adduction during stance in female runners is supported by prior research showing females having a 3° greater maximum hip adduction compared to males [56, 66, 125]. In general, females have a higher pelvis width-to-femur length ratio, resulting in greater hip adduction [126]. The normal ROM of hip adduction during running is 8-10° [52, 53], so hip ADD angles greater than 15° are indicators for injury [126, 127]. Excessive hip ADD is associated with hip ABD weakness [128]. Strengthening exercises for hip ABD muscles can be done to reduce excessive hip ADD [129, 130].

5.3 PLANTAR PRESSURE

There were no statistical differences in vertical GRF or force impulse between participant groups. These parameters were not influenced by the gender of the participant. These results are supported by studies concluding no significant gender differences in vertical GRF [131, 132] and force impulse [4]. However, Bazuelo-Ruiz et al. found greater peak vertical GRF in male runners compared to female runners [133]. The significant difference may be a result of the running speed. While Bazuelo-Ruiz et al. had participants run at 7.4 mph [133], this current study and others [131, 132] had participants run either a self-selected sub-maximal or maximal speed. This information indicates that gender differences in vertical GRF are not observed at larger ranges of running speeds.

Females displayed significantly greater plantar pressure and pressure impulse during stance phase. This result differs from a study which examined the effects of gender and shoe type on plantar pressures and found female runners had significantly lower plantar pressures in the heel for all shoe types tested [134]. In this study, female runners also had significantly lower GRF in the heel. The GRF data in the current study was not trending towards being different since the p-value was 0.364. Since pressure is equal to force per unit area and there were no statistical differences in GRFs, contact area of the participants influenced the pressure data. Prior research shows female runners have significantly higher contact area than male runners [131].

Males had significantly greater peak midfoot GRF and force impulse. This result shows that the male participants were loading more on the midfoot during the loading response, which was when the peak midfoot GRF occurred. This result is different than previous reports of no statistical differences in peak midfoot GRF and force impulse between genders. In a Hennig study, female runners trended towards greater midfoot force impulse compared to male runners [134]. Researchers have found a stronger collapse of the medial longitudinal arch leads to greater midfoot GRF while the foot is flat in stance phase [135, 136]. Since the plantar fascia provides structural support to the arch [137], it would be beneficial to determine if there is a direct correlation between plantar fascia strain and arch compression during running.

Running speed was not significantly different in the current study but the male group ran at an average of 1.0 mph faster than the female group. The differences in midfoot loading showed that a higher running speed leads to increased loading in the midfoot, which is supported by previous research [9, 11, 99]. These studies found peak midfoot GRF significantly increased as running speed increased [11, 99] and cadence increased [9]. Strike pattern also has an influence on midfoot loading, with RFS runners having significantly greater peak midfoot GRF and force impulse [138, 139].

The difference in midfoot loading could also be due to the differences in kinematics. While there were no significant differences found in sagittal plane hip ROM between males and females, males had a statistically significant negative correlation between peak midfoot GRF and hip flexion (Table *4.4.2*). This result means that male runners had more hip extension during the loading response as the midfoot reached its peak GRF. Another kinematic parameter that influences midfoot loading is ankle inversion. Females had significantly greater ankle inversion ROM compared to males. Since the female runners also had significantly less midfoot loading, it can be concluded that increased ankle inversion results in less midfoot loading. This was supported with females having a negative correlation between peak midfoot GRF, when the foot was in three zones, and ankle inversion, although it was not significant (Appendix A).

5.4 CORRELATION TESTS

In the first correlation test between peak plantar pressure and GRF and joint kinematics, females had statistically significant positive correlations between peak plantar pressure and ankle DF, knee flexion, and ankle inversion. Peak plantar pressure occurred near 60% of stance, which is at the end of MSt. At this point during stance, the body is preparing for TO, so the ankle is plantar flexing and inverting and the knee is extending. The quadriceps and PF muscles are also concentrically active to provide these motions [56]. When the peak plantar pressure is reached, the COP is anterior and lateral to the ankle and posterior to the knee [31]. The COP position creates an external DF and eversion ankle moment and knee flexion moment for the GRF. Thus, the ankle has internal PF and inversion moments and the knee has an extension moment. The positive correlations found in the female participants indicate as female runners apply more pressure, there is a higher demand on the quadriceps and PF muscles to provide the internal moments at the knee and ankle. This can result in higher joint contact forces in the ankle and knee [140]. It has been reported female runners had greater forces during TO and overall peak forces in the hamstrings and gastrocnemius, indicating a higher risk for patellofemoral pain [141].

The second correlation test compared peak joint kinematics with plantar pressure and GRF. The male participants had a significant positive correlation between peak knee flexion and plantar pressure. On average, the peak knee flexion occurred at 39% of stance, which is during IC. At this time, the COP is along the midline of the foot and power is absorbed at the knee by eccentrically active quadriceps to control the amount of flexion [56]. This positive correlation may be a result of the quadriceps activity during the stance phase. It has been reported that quadriceps activity increases as the running speed increases [142]. As running speed increases, there is greater knee flexion, thus requiring greater eccentric activity of the quadriceps to prevent rapid kick back. Another reason for the positive correlation is the vertical GRF. Even though there were no statistical differences in peak GRF in this study, males had a greater peak than females (1.88 times BW vs 1.77 times BW). There is a direct relationship between GRF and plantar pressure (Equation 1) and vertical GRF and knee flexion increase as running speed increases [31, 52, 53].

The third correlation test compared peak GRF in three zones of the foot and joint kinematics. Males had a significant negative correlation between peak midfoot GRF, when the foot was in three zones, and hip flexion. The peak midfoot GRF occurred during the IC, when the hip is extending and hip extensors are concentrically active. At IC, power is generated to provide vertical COM support and extend the hip joint [53, 56]. This negative correlation is representative of a relationship between midfoot GRF and COM support. The speed and position of the COM determines the GRF vector (direction and magnitude) [53]. As midfoot loading increases with running speed, the COM is more posteriorly directed, requiring more hip extension [143]. If the hip is not extended when landing more on the midfoot, it puts a runner at risk for a hamstring strain. This type of injury can be avoided through stretching and strengthening, warm-up, and cool-down exercises [39, 144].

The fourth correlation test compared peak GRF in ten zones of the foot and joint kinematics. The male participants had a significant negative correlation between peak first metatarsal GRF and hip ADD, peak third metatarsal GRF and ankle DF, peak fourth metatarsal GRF and ankle DF, and peak fifth metatarsal GRF and knee flexion. The peak metatarsal GRFs all occurred during MSt, which is when the hip abductors are concentrically active to raise the CL side of the pelvis. The knee is extending to provide vertical COM support and the ankle is plantar flexing to prepare for TO [56]. The negative correlation between peak first metatarsal GRF and hip ADD indicates increases in the first metatarsal GRF will require greater activation of the hip abductors, leading to potential hip ADD weakness by over-stretching the hip adductors. Weakness in the hip abductors and adductors has been associated with injuries in the ankle and foot [145]. It is also known that one risk factor for iliotibial band syndrome is increased hip ABD because it leads to greater tension near the insertion of the iliotibial band [44]. The increased GRFs in the third through fifth metatarsals require more ankle PF and knee extension, propelling the body forward and leading to an earlier TO. This may be a result of increases in running speed, which require greater ankle PF and knee extension to achieve the higher speeds [53, 146]. The increased ankle PF can create tension in the plantar fascia, leading to pain and possible rupture, as well as over-stretched or weak DF muscles [48, 122]. Excessive knee extension is a potential risk factor for hamstring strains [39] and iliotibial band syndrome [44, 147].

The fifth and sixth correlations compared running speed to peak GRF and plantar pressure, respectively. Participants showed positive correlations between the parameters, but females displayed a statistically significant positive correlation between speed and peak GRF. This correlation is representative of how female runners achieve their running speeds. Weyand et al. also examined the relationship between running speed and GRF and found that runners achieved faster running speeds by increasing the GRF [148]. This information adds to current literature, which shows that faster running speeds are associated with an increase in cadence and longer stride lengths [117, 118, 149].

5.5 FUTURE RECOMMENDATIONS

This study was performed to assess correlations between plantar pressure metrics and joint kinematics. Risk factors for running injuries can be divided into intrinsic or extrinsic factors and are dependent on joint location and whether the injury is overuse or acute [3, 15]. Proper treatment and prevention of running injuries requires understanding of how pressure metrics and joint kinematics are related to one another. The results from this study provided information on potential injury risk for runners. For future studies, a neural network model can be made to understand patterns in the plantar pressure and kinematic data. Based on results of this study, inputs for a neural network model would be peak plantar pressure for females and peak GRF in the midfoot and metatarsals for males. These models are designed to determine patterns, relationships between variables, and categorize new variables based on available data [150, 151]. Another recommendation for future studies is building a 3D kinetic model based on data from the plantar pressure treadmill. This kinetic model could be validated against data from a force treadmill. A validated kinetic model for the plantar pressure treadmill would increase its benefits in running analysis. Additional recommendations for future studies include larger sample sizes, analyzing running footwear, and different running speeds. The sample size of a study increases as its power increases [152, 153]. Power for this study was 0.79 for females and 0.64 for males, and both powers were below the minimum ideal power of 0.80. However, the drawbacks of a larger sample size are magnification of bias and increased costs for the study [154]. Future studies should also investigate how running footwear and different running speeds influence the correlations between plantar pressure and joint kinematics.

5.6 STUDY LIMITATIONS

One limitation of this study was the marker placement on top of the running shoe to construct the foot segment in the PiG model. This does not completely capture the foot motion while running because the foot is still moving within the shoe. A previous study attempted to alleviate this issue by cutting into the running shoes to place the markers on the feet. However, this affected the runners' perception of the shoe and the structure of the footwear [155]. This limitation can only be avoided if fluoroscopy is used to accurately capture the foot motion. However, fluoroscopy is not readily accessible for every research lab and is subject to additional state, facility and IRB regulations to monitor radiation exposure levels for both participants and the study team. Another limitation for this study was the running footwear of the participants. There are multiple factors of a running shoe that can influence running biomechanics [74, 85], and should be addressed in future studies. Arch type of the participants was also not examined. Gender differences in coronal plane ankle motion might be related to the arch type of the participants. Previous studies have reported kinematic and kinetic differences in low-arch and high-arch runners [74, 76, 156] and should be investigated in the future.

Additional limitations for this study were striking pattern and sample size. Although participants in this study had a RFS pattern, runners can also have a MFS or FFS pattern. Striking pattern has a significant influence on joint kinematics and plantar pressure metrics [81, 92]. Future studies could investigate how the striking pattern influences the correlations found in this study. Sample size of the participant groups was also a limitation for this study. The power for the study was below 0.8, which is the minimum desired level of power for a research study [157]. If a similar study were to be conducted at 80% power, at least 16 participants would be required in each group to draw sufficient conclusions about the correlation data.

CHAPTER 6: CONCLUSIONS

6.1 CLINICAL SIGNIFICANCE

Simultaneous measurements of plantar pressure and joint kinematics are important for running research. However, the equipment required is expensive for research labs. For example, plantar pressure devices can range between $200 and $50,000 [96]. Correlations found in this study have significance for those without access to expensive equipment. For example, coaches of track-and-field teams record their runners with a tablet or smartphone to obtain 2D kinematics. With the results of this study, coaches can analyze their runners from a video recording and make inferences about plantar pressure and GRF during the stance phase.

The results are also important in determining injury risk factors for runners. Diagnosis and treatment of running injuries is complicated due to the multi-factorial nature of the injuries [15]. The current study results suggest that females were at risk for lateral ankle sprains, hip ABD weakness, and patellofemoral pain. The male runners were susceptible to metatarsal stress fractures, hamstring strains, hip ADD weakness, plantar fasciitis, and iliotibial band syndrome. This information adds to the current body of knowledge of running injuries and will be useful to clinicians and physical therapists in diagnosing and treating these injuries.

6.2 SUMMARY

The goal of this study was to determine correlations between plantar pressure metrics and joint kinematics during the stance phase of running. The rationale for the study was that while there are many health benefits, running puts people at a high risk for LE injuries. Multiple studies have been done involving simultaneous assessment of joint kinematics and plantar pressure while running; however, there is limited research on correlations between these metrics. It was hypothesized that there are correlations present between these parameters. This information is useful not only for assessing injury risk factors for recreational runners, but also for how data is collected in future studies.

Fifteen female and eleven male recreational runners ran ten trials on a pressure treadmill. Kinematic data was collected using a motion capture system. Plantar pressure parameters investigated were peak plantar pressure, peak GRF, force impulse, and pressure impulse. The peak GRF and force impulse were determined for the entire foot, as well as three and ten zones of the foot. Joint kinematics analyzed included sagittal plane motion of the ankle, knee, and hip and coronal plane motion of the ankle and hip. Spearman rho correlation tests were used to test the hypothesis and the Mann-Whitney U test was performed to test statistical differences in joint kinematics and plantar pressure metrics. Both statistical tests were performed at a p-value of 0.05.

There were no statistical differences in the spatio-temporal parameters. Female runners had significantly greater sagittal plane ankle motion, coronal plane ankle and hip motion, peak plantar pressure, and pressure impulse compared to male runners. The male participants had significantly greater knee flexion, peak midfoot GRF, and midfoot force impulse. The hypothesis for this study was supported by the results of the Spearman rho correlation tests. Females were found to have statistically significant positive correlations between peak plantar pressure and ankle DF, knee flexion, and ankle inversion. In the males, multiple correlations were found. Males had a statistically significant negative correlation between peak midfoot GRF, when the foot was divided into three zones, and hip flexion, peak third metatarsal GRF and ankle DF, peak fourth metatarsal GRF and ankle DF, and peak fifth metatarsal and knee flexion. Statistically significant positive correlations were found in males between peak knee flexion and plantar pressure and between peak first metatarsal GRF and hip ADD.

The correlation results show how associating parameters of plantar pressure and joint kinematics make identifying running injury risk factors easier. Female runners are more susceptible to patellofemoral pain, ankle sprains, and iliotibial band syndrome. Male runners are more at risk of hamstring strains, hip ADD weakness, plantar fasciitis, and iliotibial band syndrome. Limitations of this study were sample size, marker placement on the running shoe, running footwear, arch height, and striking pattern. In future studies, researchers may consider testing plantar pressure, with insoles, on an overground run. With the correlations found in this study, researchers can make conclusions on kinematics with plantar pressure and GRF data. Future studies should also analyze the effects of running footwear and range of speeds on the correlation data, as well as developing neural network and 3D kinetic models.

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APPENDIX A: COMPLETE STATISTICAL ANALYSIS RESULTS

Table A.1 Results of Spearman rho correlation test comparing peak ground reaction force (GRF) of the entire foot and joint kinematics. DF = Dorsiflexion and ADD = Adduction.

Group	Peak GRF vs Ankle DF	Peak GRF vs Knee Flexion	Peak GRF vs Hip Flexion	Peak GRF vs Ankle Inversion	Peak GRF vs Hip ADD
Females	r_s = .042 p = .907	r_s = .321 p = .365	r_s = .309 p = .385	r_s = .152 p = .676	r_s = .394 p = .260
Males	r_s = -.350 p = .356	r_s = -.050 p = .898	r_s = .050 p = .898	r_s = -.317 p = .406	r_s = -.050 p = .898

Table A.2 Results of Spearman rho correlation test comparing peak plantar pressure (PP) of the entire foot and joint kinematics. DF = Dorsiflexion and ADD = Adduction. The yellow highlighted sections represented results that are statistically significant.

Group	Peak PP vs Ankle DF	Peak PP vs Knee Flexion	Peak PP vs Hip Flexion	Peak PP vs Ankle Inversion	Peak PP vs Hip ADD
Females	r_s = .867 p = .001	r_s = .915 p = 0.00	r_s = -.624 p = .054	r_s = .830 p = .003	r_s = -.333 p = .347
Males	r_s = -.167 p = .668	r_s = .217 p = .576	r_s = -.217 p = .576	r_s = .017 p = .966	r_s = -.283 p = .460

Table A.3 Results of Spearman rho correlation test comparing peak joint kinematics and ground reaction force (GRF). DF = Dorsiflexion and ADD = Adduction.

Group	Peak Ankle DF vs GRF	Peak Knee Flexion vs GRF	Peak Hip Flexion vs GRF	Peak Ankle Inversion vs GRF	Peak Hip ADD vs GRF
Females	r_s = .152 p = .676	r_s = -.382 p = .276	r_s = -.176 p = .627	r_s = -.224 p = .533	r_s = .503 p = .138
Males	r_s = -.100 p = .798	r_s = .600 p = .088	r_s = .133 p = .732	r_s = .200 p = .580	r_s = .133 p = .732

Table A.4 Results of Spearman rho correlation test comparing peak joint kinematics and plantar pressure (PP). DF = Dorsiflexion and ADD = Adduction. The yellow highlighted sections represent results that are statistically significant.

Group	Peak Ankle DF vs PP	Peak Knee Flexion vs PP	Peak Hip Flexion vs PP	Peak Ankle Inversion vs PP	Peak Hip ADD vs PP
Females	r_s = .442 p = .200	r_s = -.612 p = .060	r_s = -.006 p = .987	r_s = -.139 p = .701	r_s = .479 p = .162
Males	r_s = -.217 p = .576	r_s = .467 p = .025	r_s = .267 p = .488	r_s = .017 p = .966	r_s = .267 p = .488

Table A.5 Results of Spearman rho correlation test comparing peak hindfoot (HF) ground reaction force (GRF) and joint kinematics. DF = Dorsiflexion and ADD = Adduction.

Group	Peak HF GRF vs Ankle DF	Peak HF GRF vs Knee Flexion	Peak HF GRF vs Hip Flexion	Peak HF GRF vs Ankle Inversion	Peak HF GRF vs Hip ADD
Females	$r_s = -.067$ $p = .855$	$r_s = -.224$ $p = .533$	$r_s = .321$ $p = .365$	$r_s = .006$ $p = .987$	$r_s = -.430$ $p = .214$
Males	$r_s = -.233$ $p = .541$	$r_s = -.283$ $p = .460$	$r_s = -.417$ $p = .265$	$r_s = -.167$ $p = .668$	$r_s = -.317$ $p = .406$

Table A.6 Results of Spearman rho correlation test comparing peak midfoot (MF) ground reaction force (GRF) and joint kinematics. DF = Dorsiflexion and ADD = Adduction. The yellow highlighted sections represent results that are statistically significant. The yellow highlighted sections represent statistically significant results.

Group	Peak MF GRF vs Ankle DF	Peak MF GRF vs Knee Flexion	Peak MF GRF vs Hip Flexion	Peak MF GRF vs Ankle Inversion	Peak MF GRF vs Hip ADD
Females	$r_s = -.309$ $p = .385$	$r_s = -.382$ $p = .276$	$r_s = .042$ $p = .907$	$r_s = -.430$ $p = .214$	$r_s = .042$ $p = .907$
Males	$r_s = -.600$ $p = .088$	$r_s = -.217$ $p = .576$	$r_s = -.750$ $p = .020$	$r_s = -.300$ $p = .433$	$r_s = -.383$ $p = .308$

Table A 7 Results of Spearman rho correlation test comparing peak forefoot (FF) ground reaction force (GRF) and joint kinematics. DF = Dorsiflexion and ADD = Adduction.

Group	Peak FF GRF vs Ankle DF	Peak FF GRF vs Knee Flexion	Peak FF GRF vs Hip Flexion	Peak FF GRF vs Ankle Inversion	Peak FF GRF vs Hip ADD
Females	$r_s = .358$ $p = .310$	$r_s = .430$ $p = .214$	$r_s = .418$ $p = .229$	$r_s = .491$ $p = .150$	$r_s = .552$ $p = .098$
Males	$r_s = -.333$ $p = .381$	$r_s = .083$ $p = .831$	$r_s = -.500$ $p = .170$	$r_s = .217$ $p = .576$	$r_s = -.100$ $p = .798$

Table A.8 Results of Spearman rho correlation test comparing peak medial heel (HM) ground reaction force (GRF) and joint kinematics. DF = Dorsiflexion and ADD = Adduction.

Group	Peak HM GRF vs Ankle DF	Peak HM GRF vs Knee Flexion	Peak HM GRF vs Hip Flexion	Peak HM GRF vs Ankle Inversion	Peak HM GRF vs Hip ADD
Females	$r_s = .183$ $p = .637$	$r_s = .183$ $p = .637$	$r_s = .383$ $p = .308$	$r_s = .217$ $p = .576$	$r_s = .033$ $p = .932$
Males	$r_s = -.367$ $p = .332$	$r_s = -.433$ $p = .244$	$r_s = -.250$ $p = .516$	$r_s = -.183$ $p = .637$	$r_s = -.517$ $p = .154$

Table A.9 Results of Spearman rho correlation test comparing peak central heel (HC) ground reaction force (GRF) and joint kinematics. DF = Dorsiflexion and ADD = Adduction.

Group	Peak HC GRF vs Ankle DF	Peak HC GRF vs Knee Flexion	Peak HC GRF vs Hip Flexion	Peak HC GRF vs Ankle Inversion	Peak HC GRF vs Hip ADD
Females	r_s = .150 p = .700	r_s = .033 p = .932	r_s = .383 p = .308	r_s = .217 p = .576	r_s = .033 p = .932
Males	r_s = .150 p = .700	r_s = -.067 p = .865	r_s = -.333 p = .381	r_s = 0.00 p = 1.00	r_s = -.133 p = .732

Table A.10 Results of Spearman rho correlation test comparing peak lateral heel (HL) ground reaction force (GRF) and joint kinematics. DF = Dorsiflexion and ADD = Adduction.

Group	Peak HL GRF vs Ankle DF	Peak HL GRF vs Knee Flexion	Peak HL GRF vs Hip Flexion	Peak HL GRF vs Ankle Inversion	Peak HL GRF vs Hip ADD
Females	r_s = -.167 p = .668	r_s = -.467 p = .205	r_s = .183 p = .637	r_s = -.283 p = .460	r_s = -.350 p = .356
Males	r_s = .117 p = .765	r_s = -.167 p = .668	r_s = -.517 p = .154	r_s = .233 p = .546	r_s = .150 p = .700

Table A.11 Results of Spearman rho correlation test comparing peak midfoot (HF) ground reaction force (GRF) and joint kinematics. DF = Dorsiflexion and ADD = Adduction.

Group	Peak MF GRF vs Ankle DF	Peak MF GRF vs Knee Flexion	Peak MF GRF vs Hip Flexion	Peak MF GRF vs Ankle Inversion	Peak MF GRF vs Hip ADD
Females	r_s = .033 p = .932	r_s = .167 p = .668	r_s = .367 p = .332	r_s = .100 p = .798	r_s = .367 p = .332
Males	r_s = -.450 p = .224	r_s = 0.00 p = 1.00	r_s = -.650 p = .058	r_s = -.467 p = .205	r_s = -.067 p = .865

Table A.12 Results of Spearman rho correlation test comparing peak ground reaction force (GRF) of the 1st metatarsal (M1) and joint kinematics. DF = Dorsiflexion and ADD = Adduction. The yellow highlighted sections represent statistically significant results.

Group	Peak M1 GRF vs Ankle DF	Peak M1 GRF vs Knee Flexion	Peak M1 GRF vs Hip Flexion	Peak M1 GRF vs Ankle Inversion	Peak M1 GRF vs Hip ADD
Females	r_s = .033 p = .932	r_s = .017 p = .966	r_s = .017 p = .966	r_s = -.117 p = .765	r_s = .183 p = .637

Group	Peak M1 GRF vs Ankle DF	Peak M1 GRF vs Knee Flexion	Peak M1 GRF vs Hip Flexion	Peak M1 GRF vs Ankle Inversion	Peak M1 GRF vs Hip ADD
Males	r_s = .283 p = .460	r_s = .200 p = .606	r_s = -.233 p = .546	r_s = .600 p = .088	r_s = .683 p = .042

Table A.13 Results of Spearman rho correlation test comparing peak ground reaction force (GRF) of the 2nd metatarsal (M2) and joint kinematics. DF = Dorsiflexion and ADD = Adduction.

Group	Peak M2 GRF vs Ankle DF	Peak M2 GRF vs Knee Flexion	Peak M2 GRF vs Hip Flexion	Peak M2 GRF vs Ankle Inversion	Peak M2 GRF vs Hip ADD
Females	r_s = -.367 p = .332	r_s = -.333 p = .381	r_s = -.483 p = .187	r_s = -.450 p = .224	r_s = -.600 p = .088
Males	r_s = -.433 p = .244	r_s = .333 p = .381	r_s = -.583 p = .099	r_s = .250 p = .516	r_s = -.617 p = .077

Table A.14 Results of Spearman rho correlation test comparing peak ground reaction force (GRF) of the 3rd metatarsal (M3) and joint kinematics. DF = Dorsiflexion and ADD = Adduction. The yellow highlighted sections represent statistically significant results.

Group	Peak M3 GRF vs Ankle DF	Peak M3 GRF vs Knee Flexion	Peak M3 GRF vs Hip Flexion	Peak M3 GRF vs Ankle Inversion	Peak M3 GRF vs Hip ADD
Females	r_s = .017 p = .966	r_s = .017 p = .966	r_s = -.050 p = .898	r_s = -.267 p = .488	r_s = -.200 p = .606
Males	r_s = -.700 p = .036	r_s = -.050 p = .898	r_s = -.617 p = .077	r_s = -.283 p = .460	r_s = -.367 p = .332

Table A.15 Results of Spearman rho correlation test comparing peak ground reaction force (GRF) of the 4th metatarsal (M4) and joint kinematics. DF = Dorsiflexion and ADD = Adduction. The yellow highlighted sections represent statistically significant results.

Group	Peak M4 GRF vs Ankle DF	Peak M4 GRF vs Knee Flexion	Peak M4 GRF vs Hip Flexion	Peak M4 GRF vs Ankle Inversion	Peak M4 GRF vs Hip ADD
Females	r_s = -.267 p = .488	r_s = -.217 p = .576	r_s = -.233 p = .546	r_s = -.167 p = .668	r_s = .117 p = .765
Males	r_s = -.800 p = .010	r_s = .133 p = .732	r_s = -.533 p = .139	r_s = -.100 p = .798	r_s = -.283 p = .460

Table A.16 Results of Spearman rho correlation test comparing peak ground reaction force (GRF) of the 5th metatarsal (M5) and joint kinematics. DF = Dorsiflexion and ADD = Adduction. The yellow highlighted sections represent statistically significant results.

Group	Peak M5 GRF vs Ankle DF	Peak M5 GRF vs Knee Flexion	Peak M5 GRF vs Hip Flexion	Peak M5 GRF vs Ankle Inversion	Peak M5 GRF vs Hip ADD
Females	r_s = .050 p = .898	r_s = -.033 p = .932	r_s = -.217 p = .576	r_s = -.217 p = .576	r_s = .100 p = .798
Males	r_s = 0.00 p = 1.00	r_s = -.717 p = .030	r_s = -.567 p = .112	r_s = -.300 p = .433	r_s = -.533 p = .139

Table A.17 Results of Spearman rho correlation test comparing peak ground reaction force (GRF) of the toes (T) and joint kinematics. DF = Dorsiflexion and ADD = Adduction.

Group	Peak T GRF vs Ankle DF	Peak T GRF vs Knee Flexion	Peak T GRF vs Hip Flexion	Peak T GRF vs Ankle Inversion	Peak T GRF vs Hip ADD
Females	r_s = .017 p = .966	r_s = -.150 p = .700	r_s = -.383 p = .308	r_s = -.017 p = .966	r_s = -.067 p = .865
Males	r_s = -.033 p = .932	r_s = -.333 p = .381	r_s = -.017 p = .966	r_s = -.400 p = .286	r_s = .133 p = .732